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Assessment of Residual Stresses and Hole Quality on the Fatigue Behavior of Aircraft Structural Joints

Volume 2: Fastener Hole Drilling Quality and Fatigue Lives

March 2009

Final Report

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16. Abstract

A study was conducted on the effects of drilling fastener holes in 2024-T3 aircraft-quality aluminum. The effects were researched using three techniques: a comparison of four hole surface-quality metrics, x-ray diffraction, and fatigue at three stress intensities. Six production-line factor variables were considered: the experience of the operator, the use of a pilot hole, the length of the bit, the condition of the bit, the axial pressure or feed rate, and the rotational speed of the bit upon withdrawal from the hole. The four hole-quality metrics employed were surface roughness, conicality, the number of large gouge marks, and the angles of those marks. The pilot hole was found to produce the greatest overall effect on hole quality, improving hole quality with its use. X-ray diffraction was used to attempt to measure the relative residual hoop stresses induced by the six drilling factors. Tests found that specimens could not be compared using this method due to problems resulting from the combination of the specimen's geometry, hole surface quality, and the properties of the aluminum alloy. Fatigue tests were conducted at 25, 21, and 17.5 ksi on as-drilled and chemically polished specimens. These tests suggested that, although residual stresses do appear to have an effect, hole quality is the predominant factor affecting fatigue life.

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LIST OF SYMBOLS AND ABBREVIATIONS

θ	Theta, the angle between the x-ray emitter and detector
$\mu\varepsilon$	Microstrain
μm	Length in micrometers
Ψ	psi, the x-ray diffraction tilt angle
Ω	Omega, the x-ray incident beam angle
ksi	Stress in thousands of pounds per square inch
K_t	Stress-intensity factor = σ_{max} /S
MPa	Stress in MegaPascals10^6 Pascals, or 10^6 N/m^2
N	Force in Newtons
N_f	Cycles to failure
N_i	Cycles to crack initiation
N_{i1}	Cycles to initiation of first crack
N_{i2}	Cycles to initiation of a crack on the side of the hole opposite that of N_{i1}
R	Stress-intensity ratio $= S_{min}/S_{max}$
AGARD	Advisory Group for Aerospace Research and Development
ANOVA	Analysis of variance (statistical technique)
EDM	Electronic discharge machining
LED	Light-emitting diode
LT	Long transverse
NASA	National Aeronautics and Space Administration
SEM	Scanning Electron Microscope
TL	Transverse long

EXECUTIVE SUMMARY

A study was conducted on the effects of drilling fastener holes in 2024-T3 aircraft-quality aluminum. The effects were researched using three techniques: a comparison of four hole surface-quality metrics, x-ray diffraction, and fatigue at three stress intensities. Six production-line factor variables were considered: the experience of the operator, the use of a pilot hole, the length of the bit, the condition of the bit, the axial pressure or feed rate, and the rotational speed of the bit upon withdrawal from the hole. The four hole-quality metrics employed were surface roughness, conicality, the number of large gouge marks, and the angles of those marks. The pilot hole was found to produce the greatest overall effect on hole quality, improving hole quality with its use. X-ray diffraction was used to attempt to measure the relative residual hoop stresses induced by the six drilling factors. Tests found that specimens could not be compared using this method due to problems resulting from the combination of the specimen's geometry, hole surface quality, and the properties of the aluminum alloy. Fatigue tests were conducted at 25, 21, and 17.5 ksi on as-drilled and chemically polished specimens. These tests suggested that, although residual stresses do appear to have an effect, hole quality is the predominant factor affecting fatigue life.

1. INTRODUCTION.

The structural integrity of an aircraft depends upon a host of complex factors. One such factor is the joining together of the various components, whether by welding, mechanical fastening, or adhesive bonding. In particular, the joining of the fuselage skin panels to each other and to the frame provides a large portion of the structural strength for the entire aircraft. This thin layer of external material ties together and protects the fuselage and is subjected to some of the harshest conditions and highest stresses of the entire airframe. The most popular material for this application is aluminum, which is typically fastened together with rivets. These rivet holes produce regions of concentrated stress where cracks can form and grow, which are often hidden beneath the upper layer of the joint or by the head of the rivet.

The infamous Aloha Airlines Flight 243 in 1988 vividly demonstrated the importance of aircraft fastener hole fatigue. While in flight, an 18-foot-long section of the fuselage was ripped from the aircraft at 24,000 feet, killing a flight attendant and injuring 65 passengers. The incident was attributed to cracking along a row of rivets in the fuselage skin, caused by a combination of fatigue cracking and corrosion. The cracks from multiple rivet holes linked up, resulting in catastrophic failure.

The overall track record of modern commercial aviation, however, has been very positive. Flying is one of the safest forms of transportation due to high standards of both design and maintenance. In fact, many aircraft greatly outperform their designed life expectations. As an airframe ages, however, costs mount, due to increased maintenance and inspection, reducing profitability.

The aging of the world's commercial aircraft fleet has prompted the Federal Aviation Administration to establish an ongoing effort to study and monitor long-term damage effects such as fatigue cracking. The results allow the agency to provide industry with a list of maintenance and inspection concerns and to occasionally mandate procedures to ensure continued safety.

This study is a part of that effort, and seeks to increase the understanding of the present condition of in-service aircraft and to improve future design through better fatigue models. The primary concern of the study was the effects of production-line drilling procedures on fatigue life, in particular, on the formation of residual stresses and machining marks in fastener holes caused by the drilling process. It examined the interrelated effects of the beneficial compressive residual hoop stress and the deleterious surface machining marks, and showed that the hole surface-quality effects outweigh the subsurface stresses. Three methods of investigation were employed: hole surface-quality comparisons, x-ray diffraction, and fatigue testing.

Section 2 gives an overview of the concepts related to fatigue life and of the research related to this study. Section 3 details the properties of the material tested. Sections 4 through 6 explain the designs and test procedures of hole surface quality, x-ray diffraction, and fatigue life. Section 7 gives the significant results of these tests and interprets their meanings. Section 8 contains the conclusions, and section 9 recommends future work to answer new questions raised by this study.

2. BACKGROUND.

Although drilling may appear to be a simple process, perhaps due to the fact that it is so common, it is in fact deceptively complex. The drill bit has a geometrically complex helical shape and is relatively flexible along its axis. It has two cutting edges that work simultaneously inside the workpiece itself. Chips must be removed upwards through the bore, interfering with lubrication and cooling [1]. Since fuselage skins are only fractions of an inch thick, these issues are greatly reduced, but other drilling factors become important. Some of the primary factors are the material and geometry of the bit, sharpness of the bit, the workpiece material, and human factors, such as steadiness of hand, strength, experience, and even the time of day and day of the week.

The effects of drilling on the workpiece may be as complex as the drilling process itself. Although primarily a material removal process, the mechanical action of the drill also deforms the area around surface of the hole. The drill bit leaves scratches and gouges in its path, which may become stress concentrations. The surface is also strained, causing strain hardening and inducing either compressive or tensile residual stresses that extend radially outward for some distance from the bore of the hole. Some heat is generated by the process, which, upon cooling, may induce additional residual stresses, or even cause phase transformations.

Therefore, since drilling is both a common and complex machining process, research is needed to fully understand the interactions of all of these factors. Understanding these factors will bring improvements to the process and enable optimization of the factors for each application. Many studies have already been conducted, and have yielded valuable clues to the effects of drilling on the workpiece.

2.1 AGARD R-732.

A study on the effects of drilling, conducted by the North Atlantic Treaty Organization's Advisory Group for Aerospace Research and Development (AGARD) in 1988, found that there were significant differences in the fatigue lives of two sets of fastener holes drilled by independent parties [2]. Both parties drilled the holes using the same batch of material provided by the National Aeronautics and Space Administration (NASA), which were then chemically polished using the same 1-minute chemical polishing procedure to "smooth machining marks on the notch surface and to debur the edges of the notch." The holes were then tested under constant amplitude loading at R = 0 and R = -1. These tests found a large difference in the fatigue life between the sets of holes tested at R = 0, as shown in figure 2-1. In this figure, the squares, marked L-1, represent the specimens from one provider, and the x's, marked WP-1, represent the specimens from the other provider, all the specimens were polished for 1 minute. These results show that the holes lasted much longer than predicted and had a large amount of variability.

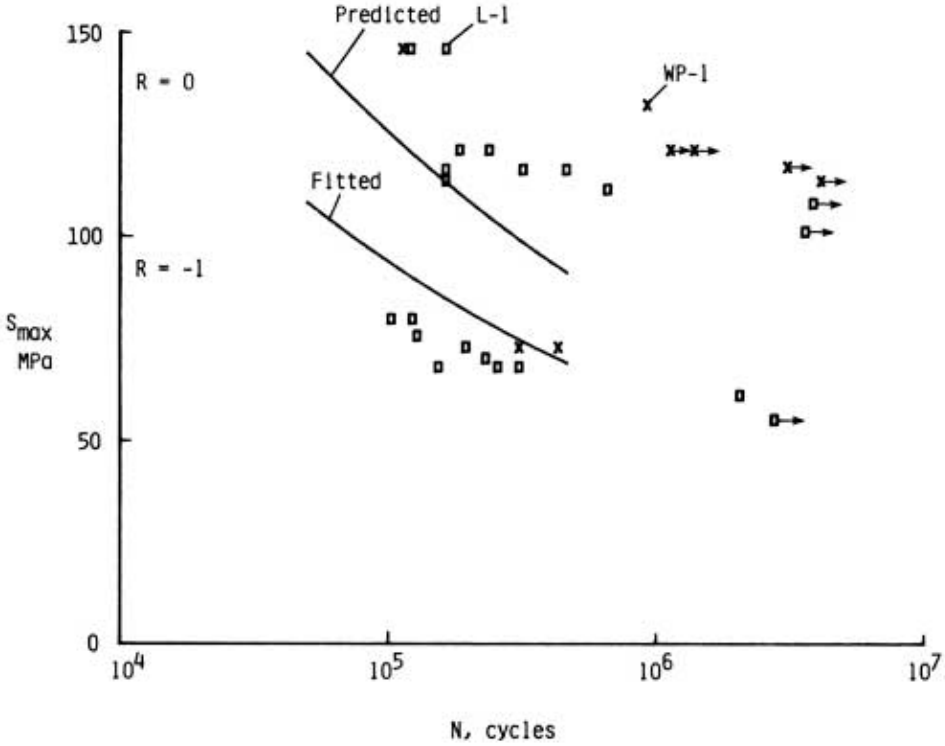


Figure 2-1. Cycles to Failure for Specimens Polished for 1 Minute [2]

The investigators suspected that machining residual stresses were the cause of these discrepancies and sought to eliminate this effect for the purpose of this study. A specimen mounted with strain gages indicated that the specimens from the different providers had compressive residual stresses of 15 MPa (2.2 ksi) for the L specimens and 70-95 MPa (10.2-13.8 ksi) for the WP specimens, which was consistent with the results from the fatigue tests.

Additional specimens from both providers were polished for either 3 or 5 minutes and then tested at R = 0 and R = -1. A baseline set of specimens was prepared using a cyclic preload-shakedown procedure that plastically yielded the notch root in decreasing intensities. As shown in figure 2-2, the specimen polished for 5 minutes (WP-5) and the preload-shakedown specimen (WP-P) closely matched the prediction in the fatigue tests, while the specimens polished for 1 and 3 minutes (L-1, WP-1, and WP-3) lasted longer in fatigue than predicted.

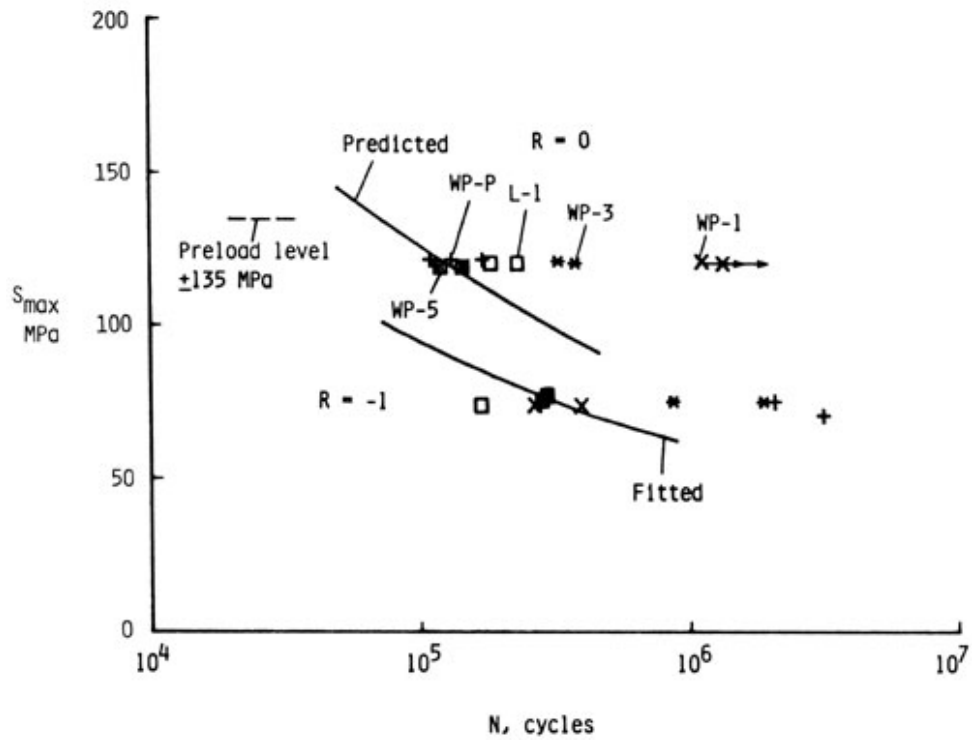


Figure 2-2. Polished and Preload-Shakedown Tests From AGARD R-732 [2]

This part of the study concluded that a 5-minute polishing procedure was required to remove any machining residual stresses from the fastener holes, in addition to the removal of machining marks and burrs. This amount of polishing removed approximately 0.0008 inch of material from all surfaces. Considering that an effect was still seen with 3-minute polishing, the residual stresses should be assumed to extend to about 0.0008 inch (about 20 microns).

2.2 RESIDUAL STRESSES.

There are many ways that fatigue life can be shortened, but only a few ways that it can be lengthened. The common methods for increasing fatigue life are plating processes such as chrome and nickel plating, thermal processes such as carburizing and nitriding, and mechanical cold-working processes such as cold rolling and shot peening. In all three methods, the benefit is primarily due to residual stresses [3].

2.2.1 Causes and Effects of Residual Stresses.

The cause of residual stresses is strain in a component to the point of localized plastic yielding. Upon removal of the stress, the volume around the yielded region attempts to return to its original position, which is resisted by the yielded region. A state of equilibrium is reached with regions of remaining tensile and compressive stresses. When the deformed region is yielded in tension, a compressive residual stress forms in that region, while the surrounding region is left in tension. Likewise, a region yielded in compression results in a tensile residual stress. The exact intensity of the residual stress depends on both the applied stress and the geometry of the region.

This process is easy to imagine with mechanical loads and, in fact, mechanically induced residual stresses are frequently induced on purpose. One common method is radial cold expansion, by which a sleeve is inserted into the hole and a tapered mandrel, slightly larger than the hole, is forced through the sleeve [4]. This results in a compressive hoop stress, which surrounds the hole in a tangential direction—the best orientation to improve fatigue life.

Residual stresses can also be thermally induced. Local heating may expand a region enough that it causes plastic deformation and, upon cooling, residual stresses form. Although this is usually an unwanted byproduct of another process, parts are sometimes carburized and nitrided to induce beneficial residual stresses, and these processes have the added benefit of increasing the strength of the surface material [3].

Heating may also change the crystallographic structure of metals, a process called phase transformation. This is of particular concern in steels, which easily transform between the austenitic and martensitic phases, causing a 4% change in volume. This change is resisted by the surrounding untransformed material, inducing considerable residual stresses [1 and 5].

In fatigue, it is the tensile loading that is of primary concern rather than compressive loading. The remote tension is effectively reduced or increased locally by the magnitude of the residual stress, depending on whether the residual stress is compressive or tensile. This is especially important at the surface of the component, since fatigue damage typically initiates at free surfaces. Therefore, compressive residual stresses are beneficial to the fatigue life of components, while tensile compressive stresses are detrimental [3].

2.2.2 Machining Variables.

In the majority of machining operations, plastic deformation of the workpiece by the cutting piece is responsible for most of the residual stresses. As the tool moves along the workpiece, it plastically deforms the surrounding volume of material. When the machined surface relaxes, the underlying material creates residual stresses near the surface. One study found that, in turning processes, the magnitude of the resultant residual stresses is largely a function of cutting speed, depth of cut, feed rate, and tool sharpness [6]. Hoop (tangential) stresses, shown in figure 2-3, were the largest stresses generated, and tool sharpness was the predominant factor, with stresses decreasing with sharpness. Residual stresses for this process were largely tensile, and linearly increased with cutting speed, linearly decreased with depth of cut, and peaked at a certain feed rate, as shown in figure 2-4. M'Saoubi, et al. [7] also found that an increase in rake angle, the angle of the cutting tool to the workpiece, led to a slight variation in the magnitude and depth of residual stresses. These variables would generally apply to drilling, although the hoop stresses would be reversed.

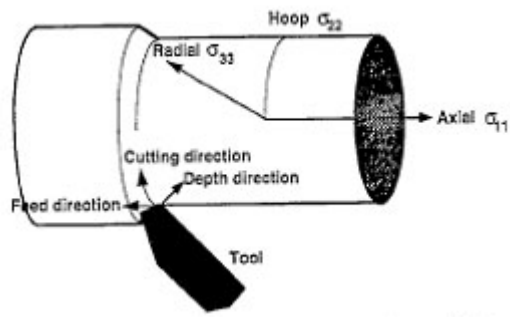


Figure 2-3. Cutting Parameters and Stress Directions for Turning [6]

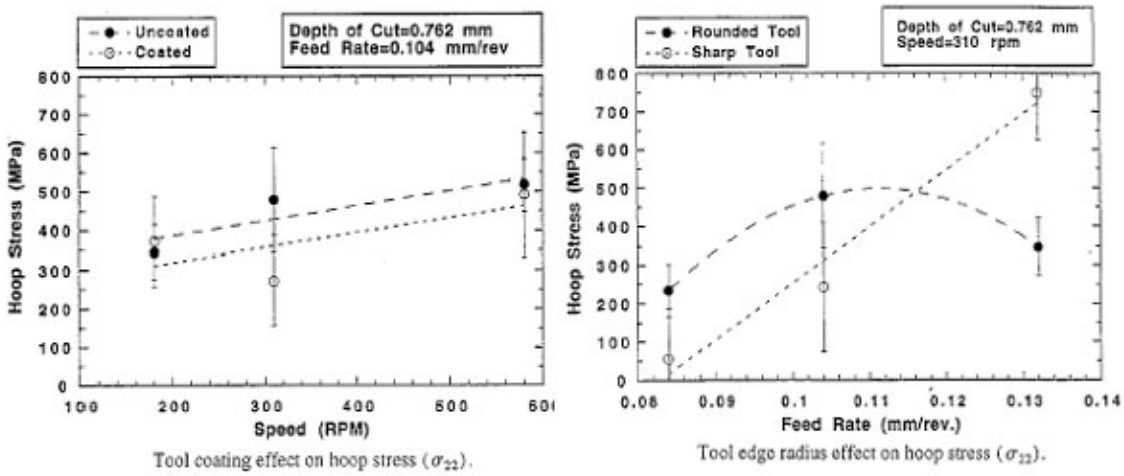


Figure 2-4. Hoop Stresses as Functions of rpm and Feed Rate [6]

Thermal expansion in machining may contribute to the formation of significant residual stresses. While this may be a factor in any machining process, it is of major importance to grinding, which generates a large temperature gradiant. The heat produced by friction creates a zone of thermal expansion, which is resisted by the cooler material around it, as shown in figure 2-5. When the stress of the expanded material exceeds the yield limit of the material, plastic deformation takes place. Cooling of the surfaces during machining can greatly reduce this effect, but a complete prediction of the residual-stress field resulting from any machining process must always take into account the thermal loading effects [8 and 9].

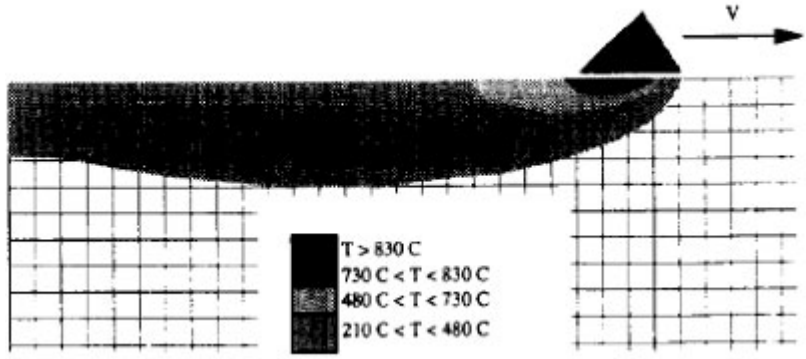


Figure 2-5. Approximated Temperature Gradient of Grinding [8]

These studies clearly show that the interactions between machining tools and the workpiece result in residual stresses. Plastic deformation and temperature gradients are the primary causes of the plastic deformations that produce these effects. Machining processes are more complex than they appear, and their effect cannot yet be accurately predicted.

2.2.3 Geometric and Material Considerations.

The exact formation of residual stresses depends upon both the geometry of the component and its constituent materials. Notches, such as fastener holes, can produce stress concentrations, which alter the effects of the remote stress. Different materials may react in very different ways, especially when it comes to temperature changes. These concerns must be taken into account to predict the residual stresses to any degree of accuracy.

As mentioned previously, residual stresses are caused by a gradient in the stress-strain field of a component. An example would be a beam subjected to a bending moment. In this case, one outer surface will experience the maximum compressive stress, while the opposite surface will experience the maximum tensile stress. Yielding will occur first at the outer surfaces, and the elastic rebounding of the deeper material will induce the residual stresses. A common stress gradient occurs at the base of a notch, called a notch root. The notch causes a stress concentration at the root, causing the root to yield first and, subsequently, experience the greatest local residual stresses when the surrounding material rebounds, as shown in figure 2-6.

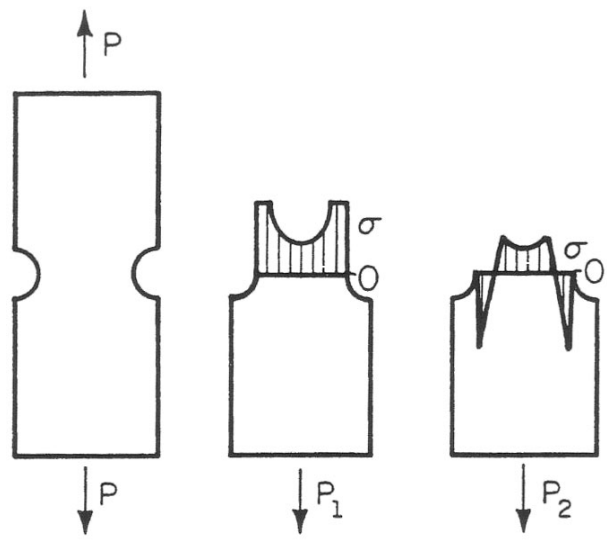


Figure 2-6. Compressive Residual-Stress Formation at a Notch Root [3]

In addition to the global effects of machining listed in section 2.2.2, local effects of the machining processes must be considered. A widely recognized local effect is the difference between entry and exit faces in radial cold expansion, described above. Despite the expandable sleeve, which serves to protect the bore of the hole from axial deformation as the mandrel is pulled through, there is still a significant difference in residual stresses between the entry and exit sides of the fastener hole (where the entry side is the one that the mandrel enters). The entry side retains lower compressive residual hoop stresses compared to the exit side. As a result, fatigue cracks usually initiate on the corners of the hole, as shown in figure 2-7. Lacarac, et al. [4] observed that in cracks less than 1 mm, specimens with cold-expanded holes grew only slightly slower than cracks of the same size in as-drilled specimens. However, cracks on the order of 2 mm showed a much slower growth rate in cold-expanded specimens. They attributed this effect to the delayed contribution of residual stresses, which only became effective as the crack penetrated through to the highly stressed exit face.

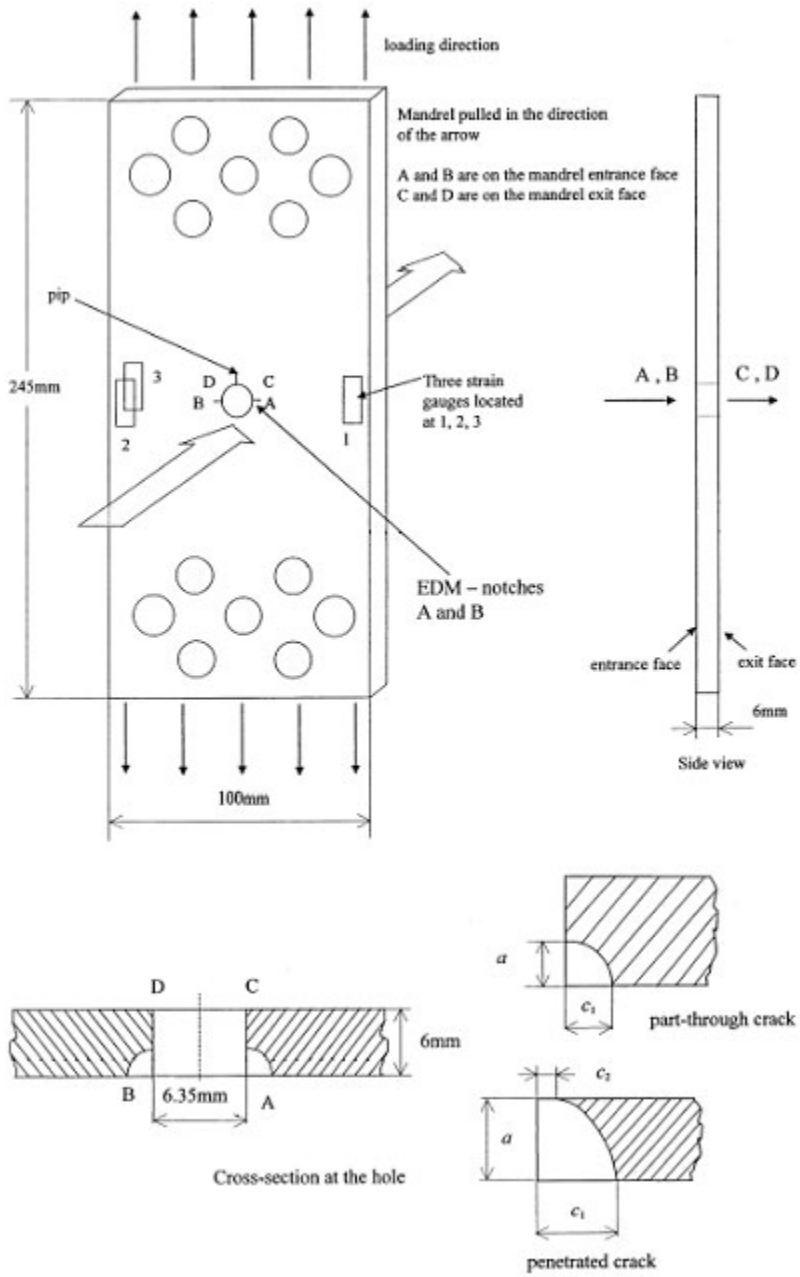


Figure 2-7. Arrangement of Cold Expansion on an Open Hole and Typical Crack Growth Geometry [4]

Finite element analysis was used to investigate the effect of cold expansion on two adjacent holes. Two models were formed based on the sequence of expansion. In one model, both holes were expanded simultaneously, while in the other, the holes were expanded separately [10]. It was found that the interaction between the holes led to increased tensile residual stresses in the region between the two holes. Additionally, there was a significant increase and shift in the formation of tensile residual stresses after sequential expansion. Representative stress fields for both models are shown in figures 2-8 and 2-9.

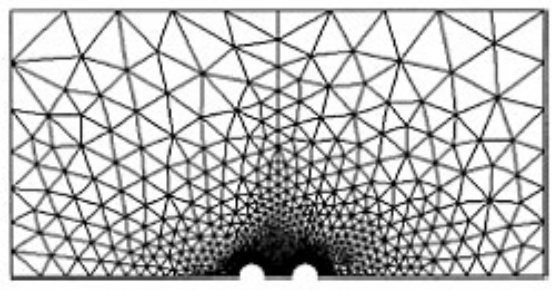


Figure 2-8. Finite Element Mesh Used for Sequential Expansion of Two Holes [10]

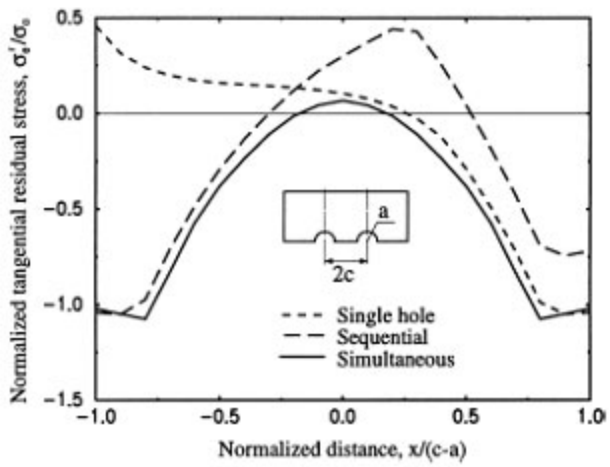


Figure 2-9. Variation of Normalized Tangential Residual Stress for Sequential and Simultaneous Expansion [10]

There may also be important variations in the formation of residual stresses among material types. For example, a recent study conducted on residual stresses resulting from abrasive waterjet machining on five different alloys found that one material achieved its maximum compressive stress below the surface, while all the others were maximized at the surface. However, the other results in the study were similar among all materials tested [11].

As mentioned in section 2.2.1, phase transformations may induce residual stresses in some materials. This is particularly true in certain steels. The transition from the austenite to martensite phase results in approximately 4% volume expansion. The austenite to pearlite transformation also produces a volume expansion [1]. Phase transformations are highly temperature- and material-dependent and are very difficult to predict.

Thus, the design and manufacturing of a component can be responsible for producing residual stresses. The exact formation of the stresses is geometry- and material-dependent and may be difficult to predict.

2.2.4 Modifying Factors.

Before a component is loaded, established techniques may be used to reduce or eliminate residual stresses. Loading conditions and high temperatures are two common means that can alter the residual-stress fields. Another phenomenon, called creep relaxation, may also reduce the residual stresses.

Exposure to high temperature is one means of altering residual stresses. When exposed to temperatures sufficiently close to the melting temperature, excitement of the atomic bonds allows the structure to become more compliant, partially or fully relaxing the residual stresses. This occurs at approximately 250°F for aluminum and 500°F for steel [3].

Additional loading may also alter the stress conditions. One study found that the application of a compressive load could significantly relax the residual stresses, and the combination of a compressive load and high-temperature exposure produced an even greater relaxation effect than the sum of these techniques separately applied. Interestingly, the application of a tensile stress during high-temperature exposure preserved the residual stresses, and high-temperature exposure during cyclic tensile loading yielded no significant increase in crack growth rate [12]. The AGARD study discussed in section 2.1 used a preload-shakedown procedure to virtually eliminate residual stresses in two specimens. The procedure consisted of 30 fully reversed (R = -1) cycles starting well above the yield stress at the notch root and reduced by 1 percent after each cycle so that the final cycles were below the elastic limit. This procedure created an alternating, continually decreasing residual-stress condition at the fatigue-critical location in the specimens [2].

Even apart from high-temperature exposure, creep relaxation of residual stresses can occur. Even after creep relaxation has occurred, significant benefit can still be gained from residual stresses,. In fact, an applied mechanical load can help retain most of the benefits of compressive residual stresses [13].

The magnitude of the load is also a factor. If a tensile load is small, it may never overcome the compressive residual stresses, and a crack may never be able to form [14]. However, if the tensile load is sufficiently large, it can almost completely relax the residual stresses, even within a few cycles and below the yield stress. As a rule of thumb, longer fatigue lives are obtained when the maximum applied stress is less than 0.5 of the yield strength [4].

The influence of the crack itself must be taken into account. As a crack grows, it forms an area of concentrated stress at its tip, shifting the stress-intensity field. During cyclic loading, the crack face expands and contracts, making stress-intensity calculations extremely complex. Simply using superposition to calculate the stress intensity becomes insufficient [4, 15, and 16]. A stress-intensity factor must be determined, which turns out to be the primary factor that determines crack growth. This stress-intensity factor is, however, modified by the residual-stress field.

Thus, the formation of residual stresses is a very complex process dependent on a number of factors. These factors include the machining process or processes, the geometry and loading history of the component, the material makeup of the component, and the temperature history.

These factors may react with each other to produce residual-stress fields different than the sum of the individual effects. A better understanding of these effects is necessary to more accurately predict the conditions in the component, which can either extend or reduce its fatigue life.

2.3 CRACK INITIATION FACTORS.

Fatigue cracks initiate at discrete locations of relative weakness or high stress. These locations may be the result of designed geometry, material imperfections, or surface irregularities. The bulk of the fatigue life of a component is spent initiating a crack at one of these locations, and failure usually occurs relatively quickly afterwards. Residual stresses can retard the initiation and growth of the crack, but once the crack initiates, it is typically just a matter of time before the component fails. Therefore, for a given design, the quality of the surface can have a great bearing on the total life of the component and should be carefully considered.

2.3.1 Hole Quality.

Even small irregularities in the surface can magnify the stress and increase the chances of crack initiation. All machining processes produce these irregularities to some degree, and drilling is no exception. In the drilling process, quality can be reduced by a number of factors, including marks on the bit, imperfections in the drilling angle, vibration, movement of the operator's hand, or chip removal.

Machining processes always produce some amount of surface roughness. In the case of drilling, the end of the drill bit penetrates the workpiece and is followed up by a cutting edge almost perpendicular to the tip. This geometry results in a sharp edge at the point that is most displaced by any axial deflection, which may cause scoring. If the bit is not perfectly orthogonal to the workpiece, or if the axis of drilling is tilted, the edges of the drill bit flutes may also result in scoring. Any marks on the flutes will scratch the surface of the bore of the hole as the bit spirals down through the workpiece.

The drill bit may also move as a whole during drilling, either through vibration or by movement of the operator's hand. This causes the bit to approach the workpiece at different angles, which may cause the sharp edge of the bit to cut into the bore of the hole. Vibrations may also cause the flutes to cut into the edge, resulting in a roughened bore surface.

Chip removal can be problematic during drilling since the chips must be removed back through the hole in the opposite direction of the drilling. These chips can become lodged between the flutes and the workpiece, resulting in rifling marks. Rifling marks are scoring marks that spiral through the hole bore.

Fastener holes can be mechanically or chemically polished to improve the surface roughness, but this is expensive and, therefore, not normally done in production, even in the case of fuselage fastener holes. Fasteners may flatten out some of the roughness and perhaps induce a compressive residual stress (or a tensile load), but larger scoring and rifling marks are likely to remain, especially if the material is strain hardened during creation.

All of these issues increase the surface roughness of the final hole. When the component is subjected to fatigue, each mark becomes a stress concentration, and a possible site for crack initiation. Larger marks create higher stress concentrations, which are more likely to initiate a crack.

2.3.2 Burrs.

As the drill bit penetrates the exit face of the workpiece and as it is removed from the workpiece, material is often deformed outward from the bore of the hole. This material, called a burr, is work-hardened and relatively brittle, as well as highly irregular in shape. These burrs may provide additional crack initiation sites.

The removal of burrs is an additional machining expense; therefore, the reduction of burr formation has been the subject of a number of investigations. Several studies have attempted to explain how burrs are created and to classify each type on the basis of their shape. One such study identified three types of exit burr shapes and attributed their creation to three similar mechanisms involving the deformation of the small volume of material at the exit face of the hole, which is shown in figure 2-10 [17]. However, this study made no mention of burrs on the entry side of the hole, and the burr formation model suggested that an entry burr was not possible. Another study by one of the same authors identified the same geometries of burrs, but also recognized the importance of the entry burr. The report stated that high feed rate, cutting speed, and tool wear increased the burr size, and that the smoothness of chip flow through the hole decreased the burr size, indicating that burr formation is more than just a small, localized exit phenomenon [18]. Yet another study developed a different burr-type classification, which was related to the presence of a burr cap—a thin remnant of material pushed aside by the drill tip. This study attributed burr formation to material properties and drill geometry, as well as the cutting conditions [19]. A finite element analysis of burr formation was conducted by another author, but assumed only local deformation of the exit material [20].

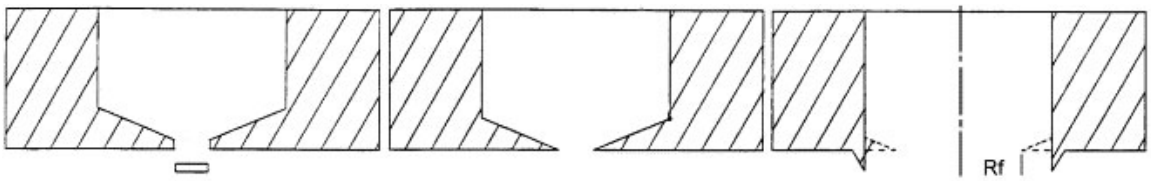


Figure 2-10. Saunders' Model of Burr Formation at the Exit Face [20]

No studies could be found that explained the formation of entry burrs or that asserted that larger-scale plasticity of the hole bore along the drilling axis contributed to burr formation. If burr formation is indeed linked to mechanisms operating deeper in the workpiece, then the shape of the burr may yield important clues to the quality of the hole. Since the burr is external, it might then provide an easy method of characterizing hole quality, and perhaps estimating fatigue life.

In aircraft assembly, fastener holes are typically not deburred, since the exit faces of the holes are usually in restrictive locations or butted up against the frame. The burr is likely crushed by riveting or fastening, but this may not remove the possibility that it remains a factor in crack initiation.

Thus, it is possible that burrs may have an effect on fatigue life, since they can serve as crack initiation sites. Several different models for burr formation were proposed, but none explained the formation of an entry burr. It is likely that a correct model of burr formation would take machining variables into account, and consider plastic deformation that occurs throughout the drilling process, rather than just at the very end.

Overall, hole quality depends on a large variety of factors, mainly grouped into machining variables and deformation processes. Hole quality is likely to have a large effect on fatigue life due to the stress concentrations that are formed by imperfections in the surface. However, hole quality is a somewhat nebulous term that could be difficult to quantify.

2.4 FINITE ELEMENT ANALYSIS.

Perhaps the greatest boon for fracture mechanics and fatigue has been the exponential improvements in computing. Numerical modeling is now a fundamental tool for complex designs, especially in the realm of aircraft design. Desktop computers are able to solve complex problems in only minutes, efficient algorithms can generate accurate solutions from fairly coarse meshes, and user-friendly software has made the technology available to any engineer [21]. These finite element programs are based on the same fundamentals of numerical methods, although they may take different approaches to fracture mechanics. In particular, the FASTRAN code works well for many fatigue crack growth problems. However, all programs have their limitations.

2.4.1 The Finite Element Method Concept.

The finite element method, a popular numerical method, approaches the modeling problem by subdividing the component. These subdivisions, called elements, may have a number of different shapes and are all connected at nodes. These nodes maintain the continuous structure of the component and are given properties to estimate the behavior of the material.

The nodes are the key to the finite element method. Each node is given an initial location in space, and boundary conditions are specified at particular nodal points to constrain the body. Stresses are then applied to the body, and the resultant strain, and therefore displacement, for each node is calculated by interpolating over each element. This allows the distribution of stress and strain to be inferred from the displacements of the nodes and the constitutive law [21].

The element geometry and size must be selected according to the component and the degree of accuracy. Of course, a finer mesh of elements requires more nodes, and therefore, more calculations and longer computing time. The boundary conditions can be incremented to simulate a dynamic system, including the release of nodal constraints to simulate crack advance.

2.4.2 FASTRAN II.

One goal of this study was to correlate experimental fatigue life with the predictions of the FASTRAN II code to account for residual-stress effects. The design of this code makes it especially suitable for the modeling of fatigue crack growth predictions.

The FASTRAN II code is based upon the Dugdale strip yield model, which accounts for plasticity-induced crack closure effects. Modifications were made to allow plastically deformed material to remain on the surface as the crack propagates. The code also accounts for variable amplitude loading effects, such as crack acceleration and retardation. Plane strain and plane stress conditions, as well as intermediate conditions, can be simulated by placing a constraint factor on tensile yielding at the crack front, thus approximating three-dimensional conditions.

These features result in very realistic results, such as different crack growth rates in the depth and length directions for three-dimensional configurations. Failure can also be modeled for brittle, ductile, and intermediate materials. Almost any loading spectrum can be modeled, including compressive and tensile loads.

A module is currently under development to incorporate pre-existing residual stresses. The results from this study will be used to verify the results of that module.

2.4.3 Limitations of Numerical Methods.

Despite the accuracy and usefulness of numerical methods, these models cannot replace experiments. Although conditions at the crack tip can be simulated, final fracture cannot be accurately predicted. These limitations are due to the continuum assumptions that the methods are based upon, which does not account for the imperfections of true engineering materials.

Continuum mechanics assumes that the material is uniform at all levels, which breaks down at the atomic level, since all materials are ultimately made up of discrete elements. The benefit of this assumption is that stress can be defined at a point, enabling the use of differential calculus. Most engineering structures are so large that the atomic effects can be disregarded without losing any significant accuracy.

Discontinuities, however, exist on scales much larger than the atomic level. All engineering materials contain voids, inclusions, microcracks, and grain boundaries. When one considers that fatigue is a crack growth phenomenon and that cracks begin on the microscopic level, these material imperfections suddenly become much larger in scale. The random nature of these imperfections prevents them from being incorporated into current numerical models.

Thus, finite element models produce sufficient predictions of the crack tip conditions, and even final failure (when the failure mode is specified) when a medium-sized crack of a given dimension is assumed, but cannot adequately predict the initiation of a crack in a component. This deficiency requires experimental testing to obtain information about the overall behavior of engineering materials due to their random, discontinuous structure.

3. MATERIAL AND SPECIMENS.

Each engineering application requires the careful selection of a suitable material. The choice of material depends on the design specifications, loading conditions, working environment, and cost. In aviation, these factors have led to the development of advanced materials from the common materials originally used in the first aircraft—from wood, to special alloys, to the new advanced composite materials that are still coming of age. In the same way, the material for this study had to be chosen to reflect the needs and realities of modern aircraft.

Material properties differ greatly, even between batches of the same alloys. It is therefore important to detail the properties of the chosen material (2024-T3 aluminum) and the characteristics of the batch of material from which the test specimens are made.

Similarly, the specimen geometry and orientation affects the fatigue life of the specimens and needs to be detailed. Specimen preparation has an effect as well and deserves consideration.

3.1 HISTORY.

Material weight has been an important consideration since the birth of aviation, as the first aircraft required lightweight construction just to get off the ground. The primary material of early airframes was wood, covered in varnished cloth. It had to be carefully protected from moisture and did not provide much toughness. Aluminum became a practical alternative after the discovery of precipitation hardening by Alfred Wilm in 1906. Several designers experimented with aluminum in the 1920s, but exfoliation corrosion was a problem until 1927, when anodizing was developed in England and Alcoa developed a cladding method [22].

Further material improvements were made largely by trial and error until the 1960s. About that time, the understanding of the properties of materials reached a point when advances could begin to be made purposefully. That purpose was provided by the desire to manufacture supersonic aircraft and by the growth of fracture mechanics, which identified specific properties governing the performance of materials. The 7050-T74 alloy was developed in the 1970s to balance the fracture toughness of 2024-T3, which had a significant weight penalty, with the high strength of 7075-T6, which was too brittle to be reliably used for tension-dominated applications. A host of other advanced alloys were then developed for specific use in wing and empennage structures. The 1980s began the development of reliable aluminum-lithium alloys with the addition of magnesium [22].

The aging of the world's commercial aircraft fleets has prompted a new focus on life-cycle cost and reliability, emphasizing the needs of commercial airlines that must not only purchase new aircraft at reasonable prices, but also cost-effectively maintain their aircraft for many years. These needs require materials that are cheap, reliable, and easily repaired.

Advanced composite materials have taken a spotlight in recent years, with their engineered load-bearing properties, ease of complex lay-up geometries, and light weight. Regardless, aluminum has remained the predominant material in the aircraft industry due to its extensive working history and material property data as well as its ease of repair and environmental friendliness

compared to composites. These reasons, along with further advances in metallurgy, should keep aluminum competitive in aircraft construction for many years to come.

3.2 MATERIAL PROPERTIES.

Aluminum was selected for this study, primarily because it is used by the majority of the current commercial aircraft fleet, as shown in table 3-1. The alloy chosen was 2024-T3. The material stock was provided by NASA and has been well documented in numerous other studies. The chemical composition of this stock of alloy is shown in table 3-2.

Table 3-1. Material Composition by Weight in Commercial Aircraft [22]

Aircraft	Aluminum (%)	Steel (%)	Titanium (%)	PMCs (%)	Other (%)
Boeing 747	81	13	4	1	1
Boeing 757	78	12	6	3	1
Boeing 767	80	14	2	3	1
Boeing 777	70	11	7	11	1
DC-10	78	14	5	1	2
MD-11	76	9	5	8	2
MD-12	70	8	4	16	2

PMC = Polymer matrix composite

Table 3-2. Chemical Composition of 2024-T3 Aluminum Alloy [2]

Element	Percent
Silicon	0.16
Iron	0.33
Copper	4.61
Manganese	0.57
Magnesium	1.51
Chromium	0.02
Zinc	0.06
Aluminum	Balance

The T3 heat treatment designation signifies solution heat treatment plus cold-working. Its major precipitates are Guinier-Preston zones, which are coherent clusters of the solute elements and are of the same crystal structure as the matrix [22]. Average tensile properties are given in table 3-3.

Table 3-3. Average Tensile Properties of 2024-T3 Aluminum Alloy Sheet [2]

Ultimate Tensile Strength	Yield Stress (0.2 percent offset)	Modulus of Elasticity	Elongation Percent
495 MPa	355 MPa	72,000 MPa	21
71.8 ksi	51.5 ksi	10,400 ksi	21

Material microstructure along the nominal dimension, perpendicular to the rolling direction, is shown in figure 3-1. Typical grain dimensions in the long transverse (LT) direction nominal crack-growth direction, 2a and c, are 25 μm and 55 μm, respectively. In the rolling direction, the typical dimension is 95 μm [2].

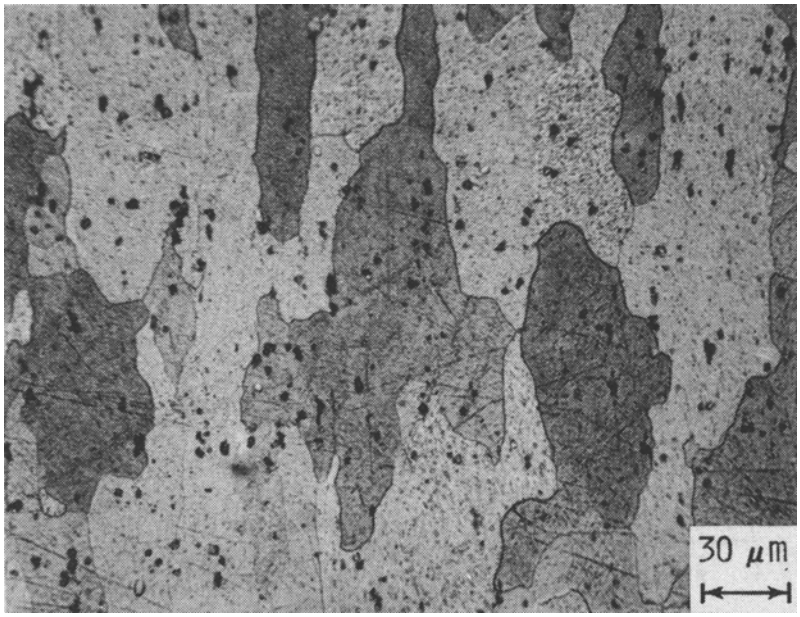


Figure 3-1. Microstructure Perpendicular to Rolling Direction [2]

3.3 SPECIMEN PROPERTIES AND GEOMETRY.

As with all the parameters of this study, the specimens were designed to represent real aircraft conditions while still reducing the variables to those that are core to fatigue life and residual stresses. The design of the specimens reflected these desires by modeling a fastener hole in tension without introducing bending forces.

3.3.1 Microstructural Orientation.

Specimens were of two different microstructural orientations. The majority of the specimens, including all hand- and machine-drilled fatigue specimens, were oriented in the LT direction. A few baseline specimens were oriented in the transverse long (TL) direction. All specimens in this report are in the LT direction unless otherwise stated.

3.3.2 Specimen Geometry.

All LT specimens had these dimensions: length L = 11.00 inches (27.94 cm), width 2W = 2.00 inches (5.08 cm), and thickness B = 0.09 inches (2.3 mm), as shown in figure 3-2. The TL specimens had the same geometry, except they were 12.00 inches long. All specimens were inscribed at the top and bottom with a unique identification number with the format A##N8-#(-TL), for example, A92N8-8 for an LT specimen or A34N7-9-TL for a TL specimen.

All specimens were filed at the edges to remove machining marks. The fatigue test specimens were through-the-thickness, center-hole specimens, as shown in figure 3-2.

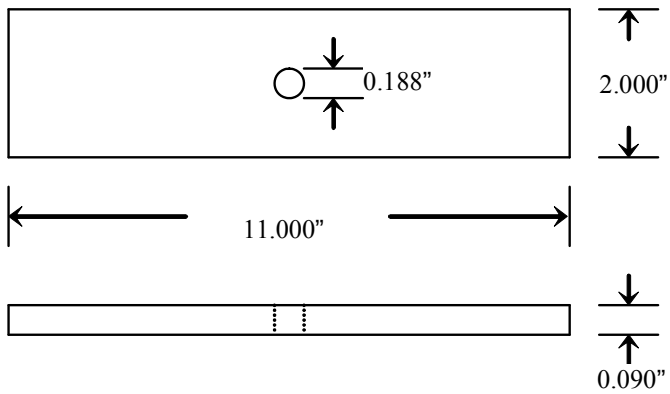


Figure 3-2. The LT Specimen Geometry

3.4 POLISHING PROCEDURE.

The baseline specimens were chemically polished in accordance with the procedure used in AGARD R-732. The solution was 80 percent (by volume) phosphoric acid, 5 percent nitric acid, 5 percent acetic acid, and 10 percent water, heated to 105°C. A small hole was drilled near the end of the polished specimen, and a hanger was inserted in the hole to suspend the specimen in the polishing solution. All polished specimens were placed in the solution for 5 minutes, which smoothed the machining marks, burrs, and significant residual stresses and mildly rounded the edges of the specimen, as shown in figure 3-3 [2].

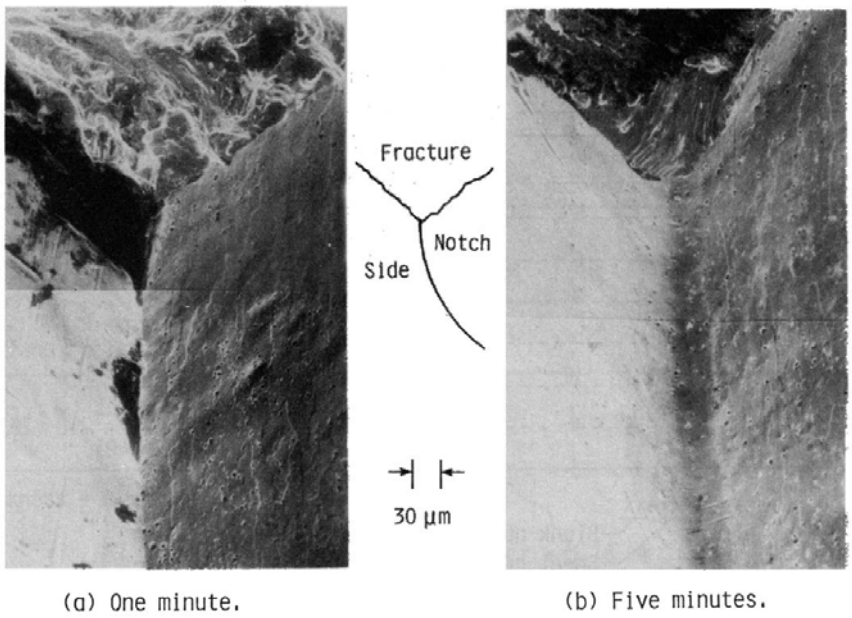


Figure 3-3. Effect of Chemical Polishing on Surface Finish [2]

4. HOLE-QUALITY EXPERIMENT.

Since hole quality is likely to have a large effect on fatigue life, a hole-quality experiment was devised. The plan was to first identify the drilling factors most likely to significantly affect hole quality. A matrix of these drilling factors was designed and the holes were drilled using combinations of these factors. The holes were then cut and prepared for microscopy. Finally, the hole surfaces were measured for hole quality and compared to each other.

One difficulty was that there was no standard method for determining hole quality. The metric or metrics needed to be established to quantify quality so that the effects of the factors could be compared objectively. Gouge marks and burrs were observed during initial inspections, and methods for incorporating them into the hole-quality metrics were developed.

There were measurement difficulties due to the curving geometry of the hole. Techniques had to be devised to accurately measure the quality according to the metrics in such a way that the curvature would not interfere.

A statistical technique called analysis of variance (ANOVA) was employed to determine the factors that produced significant differences in hole quality. The effects of the factors were compared using a normalization technique and statistical indicators of the confidence of hole-quality differences. This also enabled the correlation of hole quality with fatigue life once the fatigue tests were completed.

4.1 CHOICE OF VARIABLES.

Discussions were held with engineers and technicians at Lockheed Martin and Delta Airlines to identify factors most likely to significantly affect the fatigue life of fastener holes. The production line of an aluminum-bodied aircraft was toured, and mechanics who drilled the fastener holes were interviewed to assess the factors identified and to elicit additional information.

4.1.1 Bit Condition.

The first probable factor identified was the condition of the drill bit. A sharp, new bit should quickly and easily cut through the workpiece. This, in turn, should reduce the amount that the operator's hand strays from the drilling axis, resulting in a more cylindrical hole. A new bit should also be free of gouges and, therefore, be less likely to score the surface.

An old bit, however, may have its own benefits. An old bit would also likely cause more tangential plastic deformation of the hole bore resulting in larger compressive residual hoop stresses, which would, in turn, retard fatigue crack growth. On the other hand, an older bit would be more likely to have gouges, which would score the bore surface. The longer drilling time would allow the operator's hand to stray more and would also increase the heat generated in the hole, which may induce tensile residual hoop stresses upon cooling.

4.1.2 Pilot Hole.

It is often advantageous to drill a small diameter hole in the fastener hole location prior to drilling the final fastener hole. This smaller hole is called a pilot hole. A smaller diameter bit is easier to accurately drill in the right location since it is less likely to stray from its initial location. The pilot hole then becomes a guide for the larger diameter bit. The disadvantage is that it is more time-consuming, which becomes a major production concern when thousands of holes are drilled in the fuselage skin alone.

The use of a pilot hole may also improve the hole quality, since the primary drill bit has less material to remove. This makes for faster, straighter drilling and less wear on the bit. Less heat is generated with the primary bit, and the pilot hole may allow for better cooling and chip removal. Since the drilling time, tool wear, and material removal concerns are reduced, scoring and rifling may also be reduced.

4.1.3 Bit Length.

Two different bit lengths were typically used for fastener holes on the production line: a standard bit approximately 3.5 inches long, and a long bit approximately 6 inches long. The long bit gives the operator better control over the straightness of the drill, but it makes the tip more difficult to control when starting the hole and may deflect along its axis when pressure is applied to the bit.

4.1.4 Operator Experience.

Since fastener holes are drilled primarily by hand on the production line, human factors must come into play. It is unlikely that any two humans drill in exactly the same manner and, in fact, it is unlikely that any single human will ever drill any two holes exactly the same. The problem is that these human factors introduce a multitude of variables. Thus, to reduce the number of factors in the test matrix, it was thought that the greatest human difference in hole quality would be between an experienced operator and a novice. If the human factors are significant to hole quality, the holes from the two different operators should be very different, and the experienced operator should drill a better quality hole than the novice.

4.1.5 Bit Pressure.

It was thought that a physically larger operator would probably apply greater pressure to the drill bit than a smaller operator. This should cause greater plastic deformation, and thus, higher residual stresses in the axial direction. The greater pressure may also generate more heat, producing greater residual stresses. Additionally, if deformation in the bore of the hole affects burr formation, a higher pressure on the bit should increase the burr size.

4.1.6 Withdrawal Speed.

It was observed on the assembly line that some operators release the trigger of the drill before the bit was withdrawn from the hole, allowing the bit to slow down as it was withdrawn. If scoring or rifling is a significant issue, then a quickly rotating drill bit would leave marks almost in the

same plane as fatigue loading, while the other extreme, a bit being withdrawn after the drill was fully stopped would leave marks along the axis of the hole, which is in an ideal direction to initiate a crack.

4.1.7 Drill Block.

Another method of drilling more accurate holes is to use a tool called a drill block. This tool has many different forms, but all serve the same purpose of providing a guide for the drill bit. The drill block has a hardened steel hole of a slightly larger diameter than the bit. The bit is placed through the drill block and the tip of the bit is placed in the desired hole location. The block is then moved down to the workpiece and held firmly against it while the hole is drilled. The only hole quality differences should be that the hole is more perpendicular and cylindrical.

4.1.8 Workpiece Material.

The final factor identified was the material of the workpiece. A greater number of new aircraft construction uses alloys other than 2024-T3 aluminum for the fuselage skin. The factors in sections 4.1.1 through 4.1.7 may have different results in different materials, depending on properties such as strength, toughness, and modulus.

After reviewing the list of probable factors, two were eliminated as variables in this study. (1) The drill block was eliminated because it only served to drill a straighter hole. This function is also served by using a pilot hole. Note, the drill block and pilot hole are not used simultaneously in practice. (2) Although material type may have a significant effect, it introduced a level of complexity that was outside the scope of this project. The final choice of variables was bit condition, pilot hole, bit length, operator experience, bit pressure, and withdrawal speed.

4.2 TEST MATRICES.

To test every combination of these six variables with a minimum of three holes per variable combination, 192 holes would have to be drilled. With an estimated laboratory time of 2 hours per hole to cut, mount, polish, photograph, and measure, almost 400 hours would be required. Therefore, a fractional factorial test matrix was constructed, which allowed fewer combinations of holes to be drilled while retaining the statistical significance of the results. The variable combinations are shown in table 4-1. The matrix was designed to allow for the analysis of interactions between pairs of factors using a linear least squares fit model.

Table 4-1. Hand-Drilling Variable Combinations

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure	Bit Speed
Experienced	No	Long	New	High	Stopped
Experienced	No	Long	New	Low	Full
Experienced	No	Long	Old	High	Full
Experienced	No	Long	Old	Low	Stopped
Experienced	No	Short	New	High	Full
Experienced	No	Short	New	Low	Stopped
Experienced	No	Short	Old	High	Stopped
Experienced	No	Short	Old	Low	Full
Experienced	Yes	Long	New	High	Full
Experienced	Yes	Long	New	Low	Stopped
Experienced	Yes	Long	Old	High	Stopped
Experienced	Yes	Long	Old	Low	Full
Experienced	Yes	Short	New	High	Stopped
Experienced	Yes	Short	New	Low	Full
Experienced	Yes	Short	Old	High	Full
Experienced	Yes	Short	Old	Low	Stopped
Novice	No	Long	New	High	Stopped
Novice	No	Long	New	Low	Full
Novice	No	Long	Old	High	Full
Novice	No	Long	Old	Low	Stopped
Novice	No	Short	New	High	Full
Novice	No	Short	New	Low	Stopped
Novice	No	Short	Old	High	Stopped
Novice	No	Short	Old	Low	Full
Novice	Yes	Long	New	High	Full
Novice	Yes	Long	New	Low	Stopped
Novice	Yes	Long	Old	High	Stopped
Novice	Yes	Long	Old	Low	Full
Novice	Yes	Short	New	High	Stopped
Novice	Yes	Short	New	Low	Full
Novice	Yes	Short	Old	High	Full
Novice	Yes	Short	Old	Low	Stopped

Each variable combination was replicated three times. The resultant matrix was partially randomized to reduce both sequencing effects and operator fatigue due to frequent bit changing. The hole-quality test matrix, as it was drilled, can be found in appendix A, table A-1.

The matrix was designed to test the range of the six variables in standard practice. It was hoped that the best and worst holes that humans could drill on the assembly line would be contained within the test. To eliminate the human variables, another matrix was developed for machine

drilling. This eliminated the experienced/novice variable. The withdrawal speed variable was also eliminated because it is not standard practice, and it had little effect, as discussed in section 4.4. The pressure variable was changed to feed rate. Humans have a difficult time responding to small variations in feed rate, but respond well to pressure. Drill presses, however, are not typically setup to sense pressure, but feed rate control is standard.

A fractional factorial matrix was again employed to reduce the number of required holes. Three replicates of each variable combination were drilled. The variable combinations used in the matrix are shown in table 4-2.

Table 4-2. Machine-Drilling Variable Combinations

Bit Condition	Bit Length	Pilot Hole	Feed Rate
Old	Short	No	Low
Old	Short	Yes	High
Old	Long	No	High
Old	Long	Yes	Low
New	Short	No	High
New	Short	Yes	Low
New	Long	No	Low
New	Long	Yes	High

4.3 DRILLING PROCEDURE.

Each of the specimens to be drilled was first inscribed with a grid consisting of 3 columns running down the length and 21 rows running across the width, as shown in figure 4-1. Each of the grid intersections was punched to help the operator drill the holes squarely on the grid, which would become important when the holes were later cut in half. An identifying mark was scribed on either side of each hole, referring to the row number and column number, followed by a roman numeral referring to the specimen. For example 19-2 IV signified that the hole came from row 19, column 2 of the fourth specimen. Two of the specimens were then machine-drilled with a typical 3/32-inch pilot bit at each of the grid intersections. A punch was used to lightly mark the drilling positions in the specimens without pilot holes.

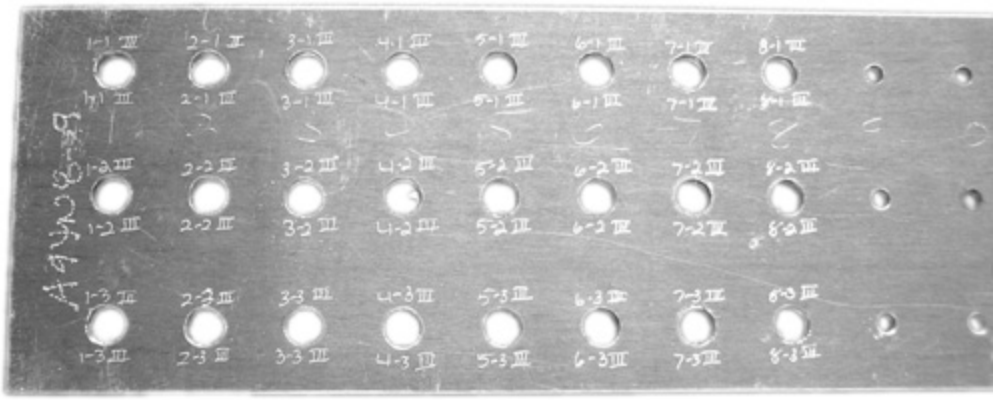


Figure 4-1. Hole-Quality Specimen Drilling Layout

All hand-drilled holes were drilled at a Lockheed Martin test facility. A constant-speed (2800 rpm) pneumatic hand drill was used, identical to those used in production, as shown in figure 4-2. The specimen to be drilled was suspended over a wooden block to catch the bit as it penetrated the specimen. It was important that the specimen did not rest on the block, as it would interfere with the formation of the burr. This was done by placing two blocks about an inch apart and centering the hole to be drilled over the gap between the blocks.

Figure 4-2. Pneumatic Hand Drill Used for Tests

All the final diameter drill bits were 3/16 inch (#10), 118 degree, high-speed twist drill bits, such as the R1SA bit from the Precision Twist Drill Company. These primary drill bits were taken from the tool crib on the assembly floor to make sure that they were typical for fastener holes. These bits were taken from a new, unopened box (not resharpened), and a different bit was used each time a bit was replaced in the drill. The used bits were chosen from a group of discarded bits from the tool crib. The bits were chosen to be similar to the new bits, but with edges dull to the touch.

There was a noticeable difference in how long it took the operators to drill the holes with and without pilot holes, and the operators commented on how much easier it was to drill with the pilot holes. There was also a noticeable difference in the time it took to drill with the old bit compared to the new bit, although less noticeable than the pilot hole. The operators also commented on how much harder it was to drill with an old bit. Additionally, a difference in the chips between the old and new bits was noticed. The new bits did produce small chips, as expected, while the old bits produced long, spiraling chips.

All the machine-drilled holes were drilled at Delta Air Lines. The drilling setup is shown in figure 4-3. The specimen was mounted in the grooves of a vise with sufficient pressure to hold the specimen firmly without causing it to bend. The short and long old drill bits were brought from the Lockheed test. For the new drill bits, bits of the same diameter were taken from the tool crib, but Delta did not have the bits in 6-inch lengths, so the long bits were cut to size. The machine that was used had high, medium, and low feed-rate speed presets, and the high and low presets were used. The high setting advanced three times faster than the low setting.

Figure 4-3. Machine-Drilling Setup

4.4 SPECIMEN PREPARATION.

After the holes were drilled, they were prepared for microscopy. Each row was cut along the hole centers by electronic discharge machining (EDM). The rows were further cut into sections of two hole halves with a grinding wheel. The sections were mounted in epoxy with the edges of the holes exposed, two holes per section, as shown in figure 4-4. These mounts were polished to one micron to remove machining marks from the EDM and to provide a good material surface. The remaining set of hole halves were also divided into sections of two, but were set aside for later analysis, and no further preparation was done to them.

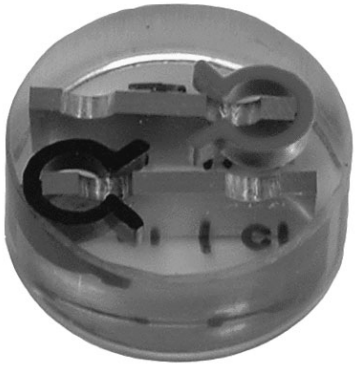


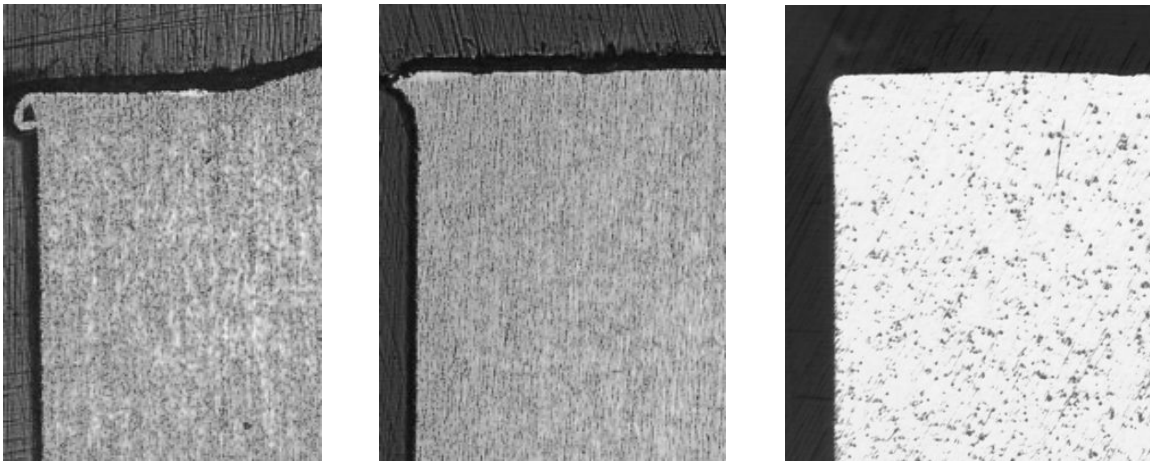
Figure 4-4. Mounted Fastener Hole Specimen

4.5 HOLE-QUALITY METRICS AND MEASUREMENT PROCEDURE.

Hole quality was judged according to four metrics: surface roughness, hole solid angle, number of gouge marks, and angle of gouge marks. In addition, burr sizes and geometries were recorded, since three distinct burr types were quickly distinguished, both at the entry and exit faces of the specimens.

4.5.1 Burr Geometry and Size.

Burrs may act as crack initiation sites, since the material hardened and became brittle. The most noticeable type of burr was called a "curling" burr, since it was long and slender and was usually found curled up like a cresting wave. The curling burr is shown in figure 4-5(a). This burr is likely the result of material from the end of the hole being pushed out and away from the bit as it exits the specimen, and probably has little correlation with residual-stress levels induced during drilling, since it would only be a local phenomenon, as modeled in figure 2-9. The second burr type was called a "triangular" burr, which is similar to the curling burr, as shown in figure 4-5(b). However, the base of the burr is wider than the length of the burr. This burr may be more indicative of residual stresses, since its base extends farther away from the bore of the hole. The width of the base indicates that there is much more involved in its formation than local plasticity at the region shown in figure 2-9. The final type of burr was called a "bulge" burr, because it was composed of a hump formed on the workpiece surface extending radially out from the bore, as shown in figure 4-5(c). This burr was thought to have a significant correlation to stresses imposed deep inside the hole, especially in the axial direction. All burr types were observed on both exit and entry faces.



(a) (b) (c)

Figure 4-5. (a) Curling Burr, (b) Triangular Burr, and (c) Bulge Burr

The desire was to develop a metric that quantified hole quality, and since the effect of the size and shape of the burr could only be speculated, as explained in section 2.3.2, it was decided that burr geometry should not be used as a metric, but only recorded and compared to fatigue life and residual stresses.

The burrs were not classified according to their size, due to the difficulty of making such a measurement. The burrs were measured according to the length that they extended out from the specimen surface, but this was judged to be a poor measure of the burr. In the case of a curling burr, a small volume of material was left protruding a relatively long distance, even if it was a relatively small curling burr. Even a very large bulge burr, however, would not extend very far from the surface, but instead, a long distance axially away from the bore of the hole. Burr length, then, depends on both the burr geometry and size. A better measure would be burr area. However, this is a difficult measurement on such a small scale with complex geometries.

The burrs were instead classified only according to type, and only the exit burrs were examined. The entry burrs were not considered because they were both relatively small and, therefore, often difficult to classify. They are also likely to be dependent on both the drilling and withdrawal phases of the process, whereas the exit burrs would be primarily dependent only on the drilling phase. Since each hole was cut in half and two sides of the hole were examined, the number of each type was recorded for each side. For example, if both sides of the hole had a triangular exit burr, the entry would be zero for the curling burr, two for the triangular burr, and zero for the bulge burr. Likewise, if one side had a triangular burr and the other a bulge burr, the entry would be zero, one, and one, respectively. Therefore, the maximum value for a particular burr type in any given hole is two, and the minimum value is zero.

4.5.2 Surface Roughness.

The curved geometry of the holes presented many challenges and eliminated the use of several common measures of surface roughness, such as contact and laser profilometry. The metric devised was the ratio of the traced surface length of the hole by the length of a straight line

drawn across the bore, as shown in figure 4-6. The holes were photographed with an optical microscope equipped with a digital camera and analyzed with Image-Pro® software. The roughness was measured on both sides of the hole and the mean value was used. To determine the endpoints of the traced and straight lines used for measurement, two edge lines were drawn along the entry and exit faces. The Image-Pro software was used to trace the surface of the hole from the intersection of the two edge lines and the surface of the hole. A straight line was then drawn between the same two intersection points used for the trace, and the length was again calculated with the Image-Pro software. The traced length was then divided by the straight-line length (producing a number ≥ 1), the process was repeated for the opposite side of the hole, and the mean of the two values was calculated.

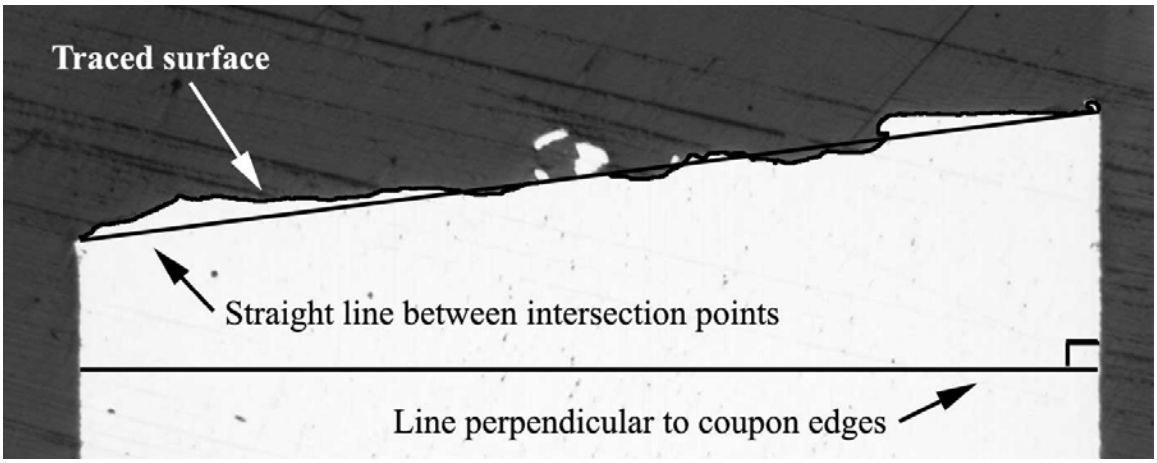


Figure 4-6. Specimen Roughness Measurement

4.5.3 Solid Angle.

It was quickly discovered that the typical hand-drilled hole was not only drilled at a slight angle from the surface normal, but also drilled wider in diameter at the entry side than the exit side so that, rather than a cylinder, the holes are more like sections of a cone. On the production line, the amount of deviation from the surface normal, or angularity, is important, because highly angular holes will not accept a rivet. This angularity is an issue of operator negligence rather than a result of drilling variables, such as bit sharpness, and is unlikely to affect fatigue life. The cone shape is the result of drill "wobble," or a circular deviation from the surface normal. As the drill penetrates the workpiece at an angle, the cutting surfaces gouge out material along the bore, leaving deep scoring marks in the surface. These marks are much deeper than machining marks produced by the drill alone, likely influencing fatigue life more than surface roughness.

Measuring this angle was straightforward. A line was added perpendicular to the two edge lines already drawn for the roughness measurements, as shown in figure 4-6, and the difference between the angle of this perpendicular line and the angle of the straight line connecting the endpoints was calculated. Again, Image-Pro automatically gave the angle measurements. Since a larger entry diameter was typical, angles in this direction were considered positive. This same angle was calculated on the opposite side of the bore, and the two angles were added together to give the resultant solid angle.

4.5.4 Gouge Marks and Plateau.

The next two metrics apply specifically to characteristic deep scoring that was found in most drilled holes. The scoring was quickly observed in the mounted holes and appeared as gouges in the surface of the hole bore, as shown in figure 4-7, and therefore was called "gouging." These gouges are much deeper than other types of scoring, and were clearly visible even without a microscope, but they spiraled down through the bore of the hole at the same angle as all the other marks. Another common characteristic noticeable to the eye is a relatively smooth, flat, and cylindrical section at the exit end of the holes. As viewed from the profile pictures, this region looked like a raised, flat region, as shown in figure 4-7, and thus was labeled a "plateau." This plateau was likely the result of the drill punching through the material at the end as soon as the tip of the drill sufficiently pierced through the specimen. This is substantiated by the absence of a plateau in the baseline set, which was machine drilled at a constant feed rate. All of these marks were of slightly varying dimensions and geometries, making a single numeric quantification of them very difficult, therefore, two simpler metrics were employed.

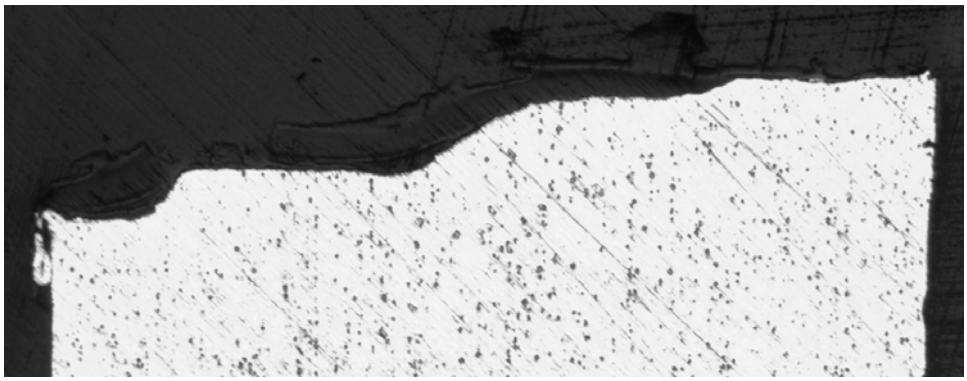


Figure 4-7. Profile Photograph of Gouge Marks and Plateau

4.5.5 Number of Gouge Marks.

The first metric for gouge marks was simply a count of the number of gouge marks in the bore surface. While there are much fewer gouge marks on the hole bores than the smaller scratches that cause general surface roughness, the gouge marks are larger and, therefore, likely to introduce higher stress concentrations. Thus, it follows that a higher number of these marks increase the likelihood of a fatigue crack initiating from one of them.

A different perspective on the hole was needed, so the unmounted hole halves were placed in the microscope so the entire bore could be viewed, rather than just the edge. The bore surface was lit from an angle to reduce glare and bring out the surface features. This readily identified the gouges, which contrasted well above the roughness of the surrounding surface, as shown in figure 4-8. The edge of the plateau region was counted as a gouge mark for this metric.

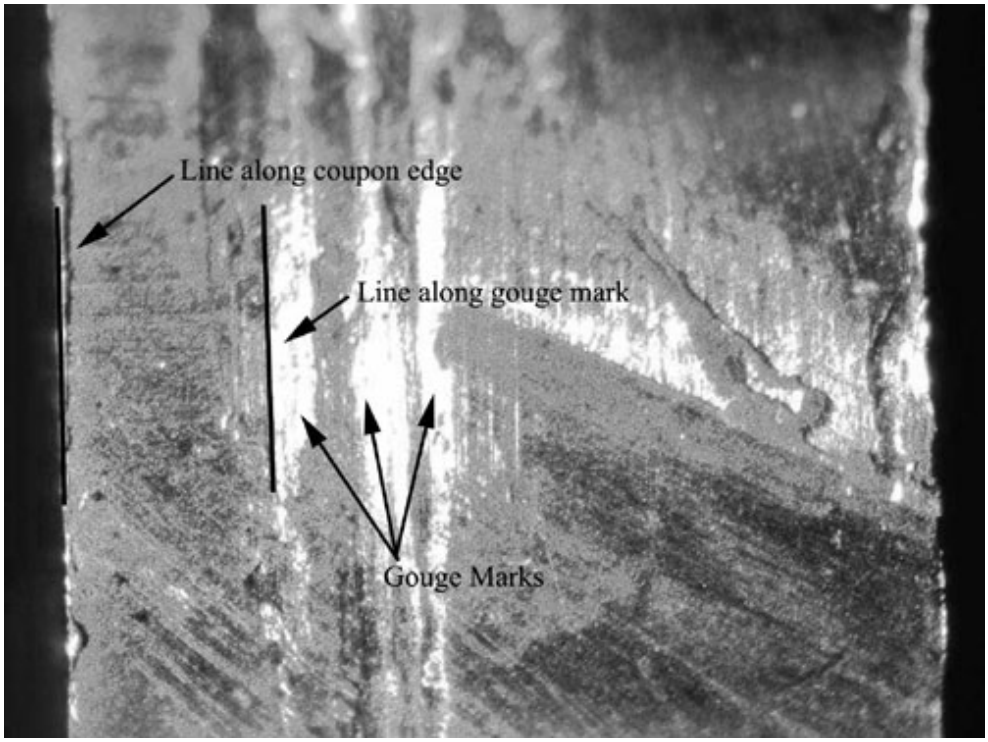


Figure 4-8. Gouge Mark Measurements

4.5.6 Gouge Mark Angle.

The second metric measured the angle of the gouges. As the angle approaches 90 degrees, or the drilling axis, the gouge becomes perpendicular to the loading axis, maximizing its effect. At 0 degrees, the gouge is oriented along the loading axis, and has minimal effect.

To measure this angle, the hole was mounted according to the gouge mark count, and the bore was photographed, as shown in figure 4-8. Using the ImagePro software, a line was drawn along one face of the specimen, and another line was drawn along a gouge mark. The difference between the angles of the two lines was calculated by the software and recorded as the value for this metric.

4.6 STATISTICAL ANALYSIS.

To compare such a complex combination of factors, a careful use of statistical techniques was necessary. First, each combination of factor and metric variable was analyzed. The factors were then compared to each other for each metric. A method of normalizing each metric according to its amount of variability was then employed. This allowed an overall comparison and ranking of the factors.

4.6.1 Ranking of Individual Metric Variables.

The analysis was simplified somewhat by using a polar matrix construction in which each factor used a high/low or on/off setting, which simulated the range of each factor under typical

assembly line conditions. For example, each operator applied either the highest or lowest realistic amount of pressure to the drill that he could. This allows the range of each factor's effect on each metric, or variable, to be calculated. To compute this range, the entire population of holes is sorted according to each factor, and the mean of each setting is calculated.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{4-1}$$

The difference in means is then calculated, and the absolute value yields the desired result. For example, all the holes were sorted according to whether a pilot hole was used, the average roughness was calculated for those holes that had a pilot hole and for those holes that did not, and the lower average value was subtracted from the higher average value. The factors are then ranked according to their difference in means. This process is repeated for each metric.

$$\text{Difference in means} = \bar{x} - \bar{y} \tag{4-2}$$

4.6.2 Normalization.

The difference in means allows the comparison of the different factor pairs for a given metric. It would, however, be more useful to compare the factor pairs across the set of metrics. To do this, the differences of means are divided by the pooled standard deviation of the two variables. The pooled standard deviation, s_p, is found using the following equation:

$$s_p = \sqrt{\frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}} \tag{4-3}$$

where s_x is the standard deviation of the first population, given by:

$$s_x = \sqrt{\frac{\sum (x - \bar{x})^2}{n-1}} \tag{4-4}$$

where n is the number of specimens in the population and s_y is likewise the standard deviation of the second population with number of specimens m. This pooled standard deviation yields a slightly more accurate result than would be achieved by dividing by the standard deviation of the entire population.

After the metrics have been normalized, the average of the variable values for each factor pair is calculated. The factors can then be ranked according to the amount of difference that each factor induces.

4.6.3 *p*-Value.

The *p*-value is a useful statistic for such analyses. It offers a convenient method for evaluating the difference produced by a factor. If the value is small, one can be reasonably confident that the factor produces a significant change in the dependent variable. This allows the investigator to boil all the variability down into a single number.

The *p*-value is the probability that there is, in fact, no difference between the variable means. A value of 0.10 or less is considered significant for most analyses. For a pooled variance procedure, the *p*-value is calculated with the *t*-statistic, which is computed by:

$$t = \frac{\bar{x} - \bar{y}}{s_p \sqrt{\frac{1}{n} + \frac{1}{m}}} \tag{4-5}$$

The *p*-value is then:

$$p\text{-value} = 2 \times P\left(X > |t|\right) \tag{4-6}$$

A word of caution should be given about the application of the *p*-value. Statistics are tools for making statements with a given amount of certainty, but are based on uncertainty and, therefore, can never be used to make a statement with absolute certainty. The specific use of this particular statistic is based upon the null hypothesis, which is that there is no difference in the specimen means. A *p*-value of 0.05 can be interpreted by saying, "There is a 5% chance that there really is no difference in the specimen means." It cannot be used to make the statement that a difference does exist, since there is always such a chance, no matter how small. The *p*-value does, however, provide a convenient measure of the amount of variation in the difference of means.

4.6.4 Confidence Intervals.

The significance of the difference of means can also be evaluated graphically using confidence intervals. A confidence interval shows the range of values that the mean may have with a given degree of confidence. An example is shown in table 4-3. In this example, the factor variables are listed under the "Level" column, the number of specimens in each population is listed in the "N" column, the mean value for each population is shown in the "Mean" column, and the "StDev" column gives the respective standard deviations. The confidence intervals are shown at the right of the table. The experimental mean value is shown with an asterisk at the center of the confidence intervals, and the range of the values that the mean may take with a 95% probability (the confidence chosen for all confidence intervals in this report) is represented by the dashes enclosed in parentheses. The mean value of the "Long" level, then, lies between about 4.5 and 6.2.

Table 4-3. Specimen Confidence Interval

```
Level       N      Mean     StDev  ------+---------+---------+---------+
Long       47     5.332     2.863   (--------*---------)
Short      47     7.162     4.920                  (---------*--------)
                                    ------+---------+---------+---------+
                                        4.8       6.0       7.2       8.4
```

The equation for calculating the confidence interval is given by:

$$\mu \in \left(\overline{x} - \frac{t_{\alpha/2,n-1} s}{\sqrt{n}}, \overline{x} + \frac{t_{\alpha/2,n-1} s}{\sqrt{n}} \right) \tag{4-7}$$

where μ is the actual mean value of the population, $\overline{x}$ is the experimental mean value, $t_{\alpha/2,n-1}$ is the student's *t*-distribution with α the confidence (0.05 for 95% confidence) and *n* the number of specimens in the population, and *s* is the experimental standard deviation. For the set in this example, the number of specimens is the same, and thus, the *t*-distributions are equivalent. The confidence intervals, then, are proportional to $s/\sqrt{n}$ so that the intervals increase with the standard deviation and decrease with the square of the number of specimens.

The example in table 4-3 has overlapping intervals, demonstrating that it is possible that there is, in fact, no difference in means (or even an opposite difference). However, the means are assumed to have a *t*-distribution, which is very similar to the normal distribution, and in fact, reduces to the normal distribution as the number of specimens approaches infinity. With such a distribution, the true mean is much more likely to fall closer to the experimental mean than the edge of the confidence interval. This is reflected by the *p*-value, which for this example is 0.030, reflecting that there is a 3% chance that there really is no difference in means.

Appendix B contains the statistical analyses for a large variety of factor combinations. The significant confidence intervals are duplicated in section 7, tables 7-1 and 7-2, with minor changes for readability. The "Level" columns are renamed "Factor," and the factor names are expanded for clarity. The "N" columns were deleted, since the number of specimens is already reflected in the standard deviation; and the *p*-values are included in the tables, since they are such meaningful statistics.

Thus, confidence intervals include a lot of information in a compact form that is easy to interpret visually. They are used extensively in the discussions of the experimental results because they offer such a wealth of statistical information.

5. X-RAY DIFFRACTION.

X-ray diffraction is a nondestructive technique that can be used to measure residual stresses in metals. It was employed in this study to attempt to measure the relative residual hoop stresses to compare the effects of the drilling factors listed in section 4. This section describes the principles of the technique and the experimental methods employed in this study.

5.1 THE X-RAY DIFFRACTION TECHNIQUE.

X-ray diffraction, in its essence, measures the intensity of rays diffracted from crystallographic planes. Figure 5-1 shows the principle of x-ray diffraction, in which an incident beam enters a crystal, strikes the atoms arranged in lattice planes, and is diffracted back through the material. At most incident angles, the diffracted rays destructively interfere with each other and cancel out, but diffract out through the lattice planes without interference at certain principal angles that are unique to each material. If one irradiates a crystal with an x-ray beam at a large range of incident angles and places a detector at corresponding angles of incidence, a graph of the intensity of the detected rays versus the angle of incidence will result in peaks at the principal angles, as shown in figure 5-2.

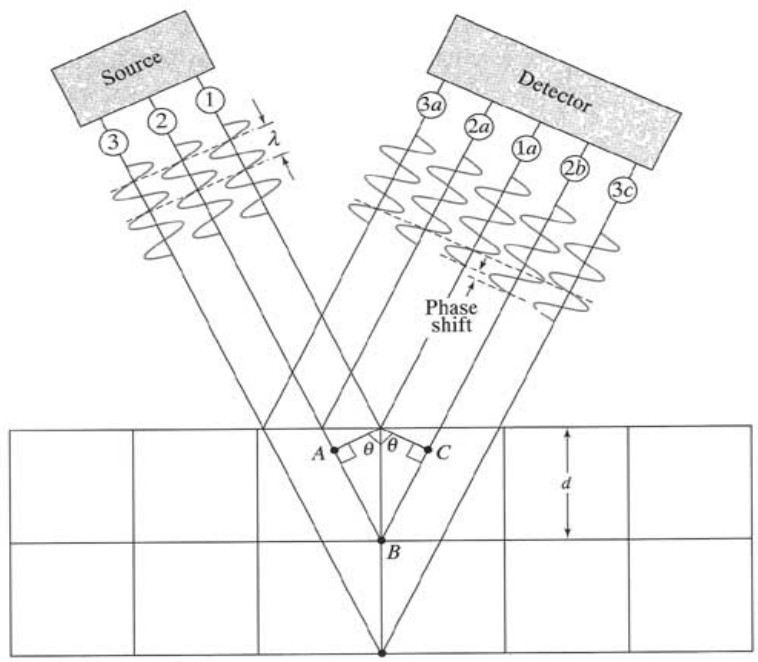


Figure 5-1. The Principle of X-Ray Diffraction [23]

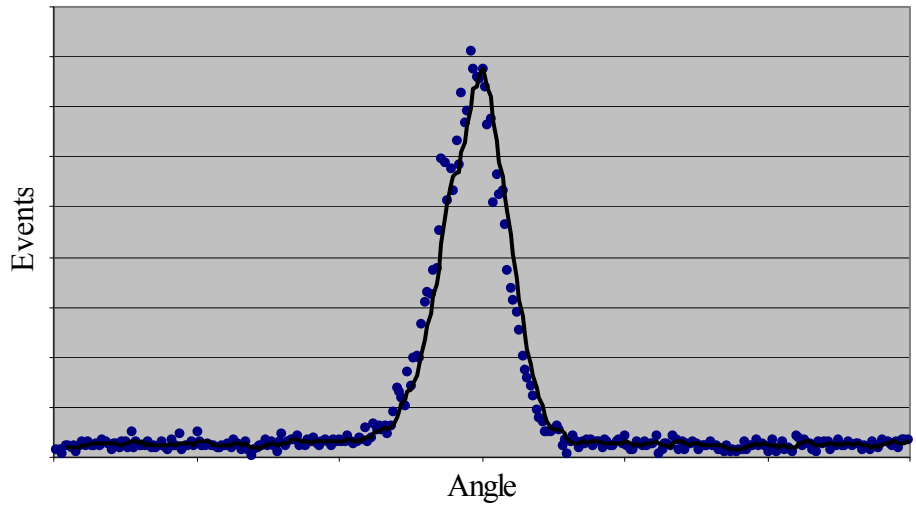


Figure 5-2. Specimen Diffraction Line

A uniform stress applied to a bulk material strains the lattice planes and increases the distance between the planes in the direction of the stress. This uniform strain results in a shift of the corresponding peaks on the diffraction line, as shown in figure 5-3(a) and (b). This shift gives a measurement of the relative strain, and therefore stress, applied to the material.

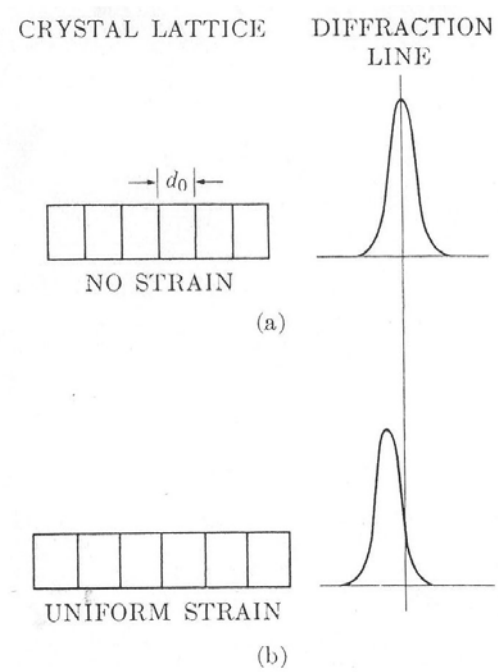


Figure 5-3. Diffraction Lines of (a) Unstrained and (b) Strained Lattices [24]

Figure 5-1 is simplified, because most metals form a polycrystalline structure with the lattice planes of the crystals oriented in random directions. These crystals are generally very small in

comparison to the bulk material, and an x-ray beam irradiating a bulk material will strike a number of crystals oriented parallel to the specimen surface, as shown in figure 5-4.

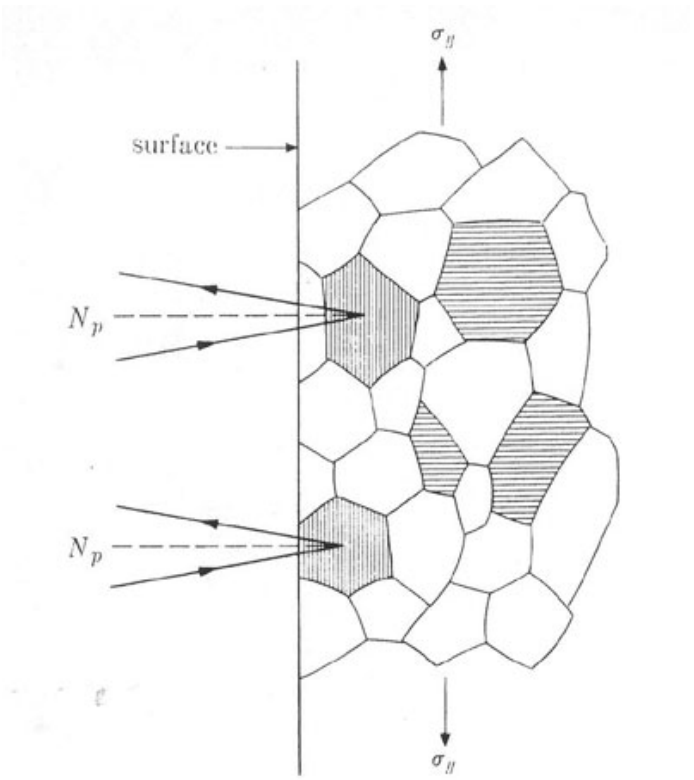


Figure 5-4. Diffraction of a Bulk Material Specimen

5.2 DESIGN OF EXPERIMENT.

The unmounted hole halves from the hole-quality experiment provided the specimen set for the x-ray diffraction experiment. Both the hand- and machine-drilled holes were used. One specimen from each combination of hand- and machine-drilling factor variables was used, as well as one polished specimen each of the LT and TL directions. This would limit the number of specimens to be tested while still providing a sufficiently large specimen population.

5.3 EXPERIMENTAL PROCEDURE.

The specimens were mounted into the x-ray goniometer stage such that the length of the specimen was vertical (the y-direction), the width was horizontal (x direction), and the depth protruded out of the stage in the z direction, as shown in figure 5-5. Rotation about the x axis is the Ψ (psi) angle, and rotation about the y axis is the 2θ/Ω (2 Theta/Omega) angle.

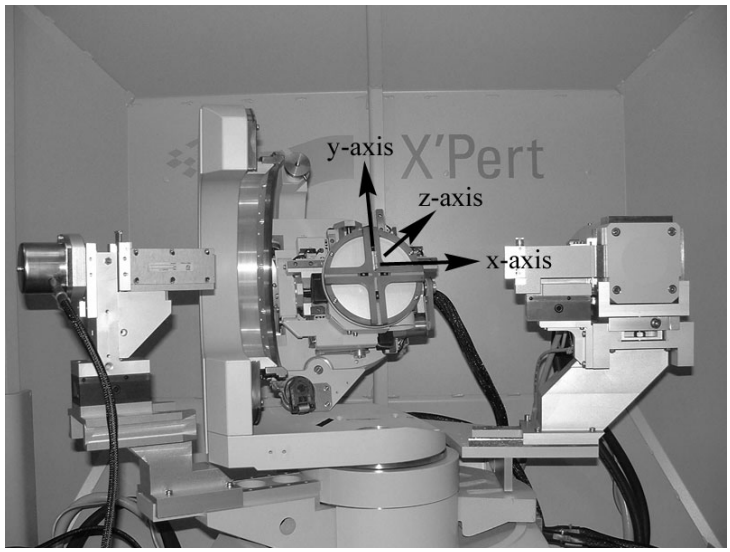
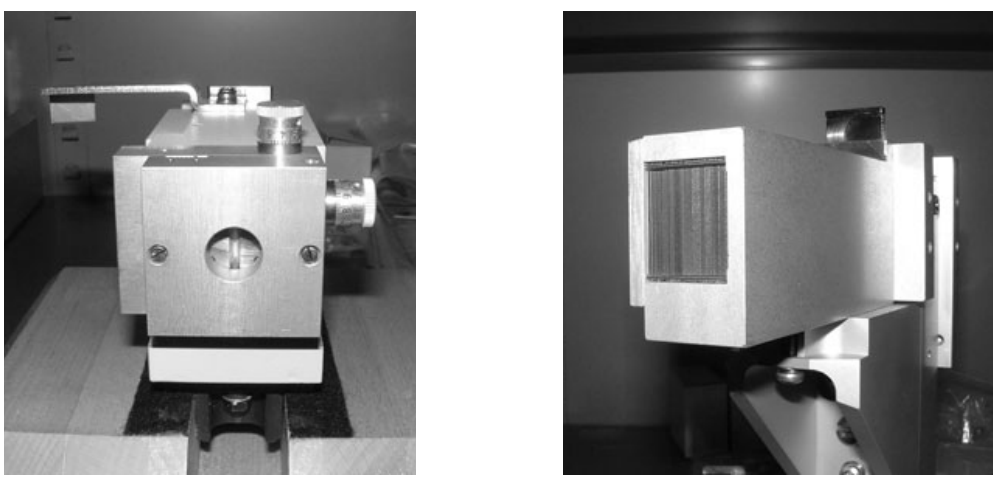


Figure 5-5. X-Ray Machine Coordinates

The x-ray beam optics were specially chosen for the specimen geometry. The Cu-kα x-ray (x-ray emitted from the k alpha shell of copper) tube was rotated to produce a spot beam, which allowed the entire beam intensity to be focused in a smaller area, rather than spread out over a line, which is typical. To optimize the height and width of the beam, a crossed-slits collimator (figure 5.6(a)) was employed, which allowed the beam size to be adjusted both vertically and horizontally from 0 to 10 mm at increments of 0.01 mm. A nickel attenuator was inserted into the crossed-slits collimator to prevent damage to the detector. The specimen stage was also aluminum, and so a parallel plate collimator (figure 5-6(b)) with a 0.027-mm slit was chosen for the detector to reduce the chance of collecting signals from the stage.

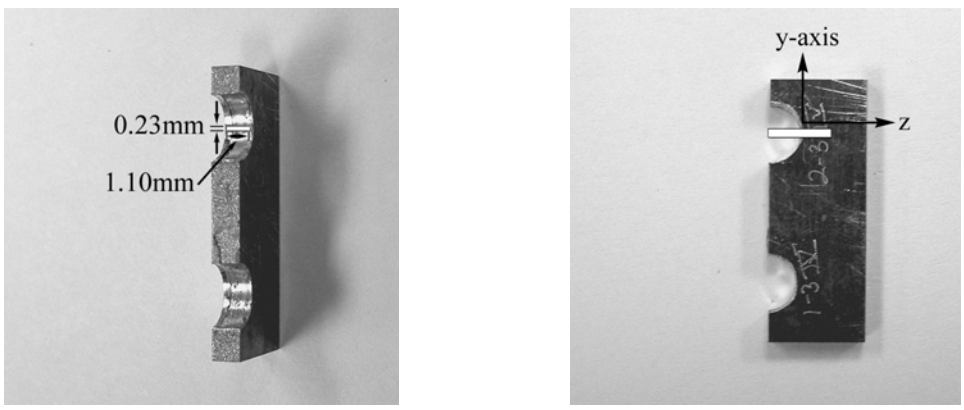


(a) (b)

Figure 5-6. (a) Crossed-Slits Collimator and (b) Parallel Plate Collimator

The placement of the beam on the specimen is shown in figure 5-7. The x-ray beam was directed into the center of the hole half to minimize any hoop stress relaxation due to cutting the

hole in half. The nominal beam cross-section was 0.25 mm^2, which was determined by reducing the beam size to the minimum allowable to clearly distinguish the peaks above the signal noise. Flat specimen surfaces are preferred so the incident beam angle is the same throughout the beam cross-section. The curved geometry of the hole, therefore, presented a continuously variable angle of incidence. To reduce this effect, the beam width was maximized so the height could be reduced to the minimum amount possible, while still retaining the nominal cross-section. In aluminum, the [111] plane gives the strongest diffraction, corresponding to a principal angle of 38.47 degrees. At a 38-degree angle, the incident beam spot width will be about 1.6 times the emitted width. Because of this, the width of the emitted beam was maximized at 1.1 mm, or about 0.043 inch, which corresponds to an incident beam spot width of about 0.070 inch, allowing 0.01 inch on either side of the beam for specimen nonuniformity, misalignment of the beam, and plane stress conditions at the free surfaces. To maintain the 0.25 mm^2 spot cross-section, the height of the emitted beam spot was set at 0.23 mm.



(a) (b)

Figure 5-7. (a) Placement and (b) Alignment of Exaggerated X-Ray Beam

Before a specimen could be scanned, it needed to be aligned and the system optimized. The specimen was loaded onto the stage as shown in figure 5-5. The specimen was always offset in the x direction by 0.84 mm, which was first accounted for in the alignment. The x-ray beam shutter was then opened and the intensity was noted. To center the beam horizontally, the specimen was adjusted along the z axis until the intensity was halved, as shown in figure 5-7(b). To center the beam vertically, the specimen was adjusted along the y axis until the intensity was maximized. The z axis was then adjusted again until the intensity was half of the original value. To align the system, a 2θ scan was run in 1 degree about the current 0 degree position, and the system was offset to match the diffraction line peak. An Ω scan was then run in 6 degrees about the current position, and the system was again offset to match the peak. Finally, an $\Omega/2\theta$ scan was run in 1 degree about the 38.47-degree principal angle, and 2θ was offset to half of Ω.

Once this was accomplished, a residual-stress scan could be run. Scans were conducted by varying the $2\theta/\Omega$ angles, and tilting the specimen at nine different Ψ angles. The peaks of each of the nine resulting curves were identified, and the corresponding lattice distance, or *d*-spacing, was recorded. The results were plotted as $\sin^2\Psi$ versus *d*, and the angle of the resultant slope represented the relative residual stress.

6. FATIGUE TESTING.

The fatigue tests are the capstone of this study, since the ultimate objective was to assess the fatigue life of aircraft fastener holes. The first goal of the tests was to compare the fatigue life of as-drilled holes to the holes polished in accordance with the AGARD R-732 procedure. The second goal was to compare the fatigue effects of the factors from the hole-quality study.

These tests also had to answer a number of different questions while making efficient use of time and material. The test parameters needed to be consistent with those of the AGARD R-732 study, as discussed in section 2.1.1, which concluded that drilling induced significant compressive residual hoop stresses that could be removed through a chemical-polishing procedure. Consistency in loading parameters would enable the comparison of the results of this study with those of the AGARD study. The tests also needed to represent the conditions to which the actual production fastener holes are subjected in order to provide meaningful application to the industry.

6.1 DESIGN OF EXPERIMENTS.

The fatigue tests were broken into two segments. The first segment tested only as-drilled and polished specimens. In the second segment, rivets were inserted into the specimen holes to assess whether the fastening process eliminated drilling effects or modified them.

The first test was designed to investigate the effect of residual stresses, which were assumed to exist in the as-drilled holes. Two factors were chosen that resulted in four possible combinations. Six replicates of each combination were drilled to provide statistical significance of the results while allowing for a variety of loading conditions. This yielded 24 holes, which were less than one-third of the available test specimens, and were able to be fatigue tested in a reasonable amount of time.

The three most significant hole-quality factors were (1) pilot hole, (2) operator, and (3) bit condition, as discussed in section 7.1. The use of a pilot hole resulted in the largest hole-quality variations, and was thus chosen as a factor for the fatigue tests. The operator factor was included in the hole-quality experiment to represent the human factors involved in drilling. These factors are likely to be extremely complex and out of the scope of this study. The operator factor was, therefore, eliminated as a factor for this test matrix. The drill bit condition also resulted in significant variations in hole quality, and it was also suspected that a dull drill bit would induce greater residual stresses than a sharp bit. Bit condition was, therefore, chosen as the second factor for the first test.

Due to the small number of specimens to be prepared, a factorial matrix was not required. The four factor combinations are shown in table 6-1. The 12 specimens that used a pilot hole were predrilled before the fastener holes were drilled. All 24 specimens were randomized to reduce sequencing effects, and the randomized matrix is shown in table 6-2.

Table 6-1. Fatigue Test As-Drilled Factor Combinations

Bit Condition	Pilot Hole
New	Yes
New	No
Old	Yes
Old	No

Table 6-2. Randomized Hand-Drilling Matrix

Bit Condition	Pilot Hole	Specimen
Old	Yes	A96N8-6
New	No	A93N8-4
New	Yes	A91N8-14
New	No	A95N8-2
Old	No	A91N8-8
New	Yes	A94N8-12
New	No	A96N8-3
Old	Yes	A89N8-3
Old	No	A95N8-3
New	No	A89N8-9
New	Yes	A91N8-3
Old	Yes	A95N8-14

Bit Condition	Pilot Hole	Specimen
New	Yes	A90N8-10
Old	Yes	A94N8-6
Old	Yes	A93N8-3
Old	Yes	A93N8-15
New	Yes	A94N8-14
New	Yes	A91N8-12
New	No	A90N8-15
Old	No	A96N8-10
Old	No	A93N8-8
Old	No	A89N8-14
Old	No	A93N8-10
New	No	A95N8-7

All the as-drilled specimens provided were in the LT orientation. Specimens polished according to the AGARD R-732 5-minute polishing procedure were provided in both the LT and TL orientations for the purpose of establishing a baseline comparable to the AGARD study. Another set of machine-drilled specimens was prepared at Delta Airlines for the purpose of establishing an as-drilled baseline. The factor combinations for the machine-drilled specimens were chosen based on the theoretical best-quality hole parameters—short bit, low feed rate, and with a pilot hole. Since it was unknown whether an old bit would increase the fatigue life, both an old bit and new bit were used. Loads were chosen to be the same as those in the AGARD study, which were $R = 0$ with a maximum remote stress of 17.5, 21, and 25 ksi. The complete test matrix is shown in table 6-3.

Table 6-3. Fatigue Test Matrix

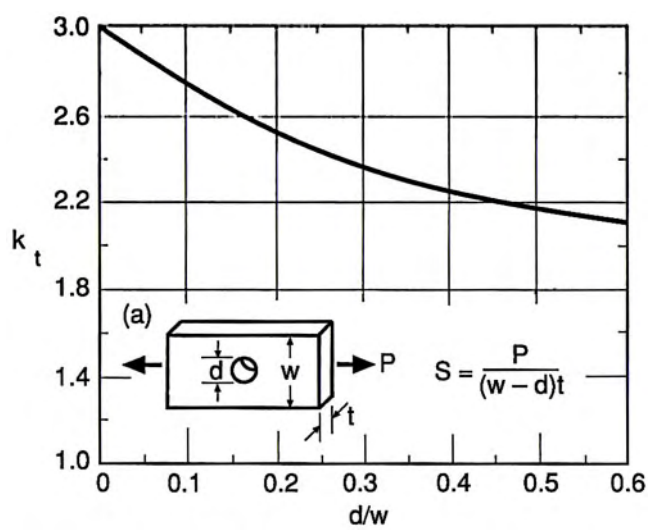
Specimen Type	Max Load (ksi)	Number
Polished, LT	17.5	2
Polished, TL	17.5	2
Hand-Drilled, New Bit, No Pilot Hole	17.5	1
Hand-Drilled, New Bit, Pilot Hole	17.5	1
Hand-Drilled, Old Bit, No Pilot Hole	17.5	1
Hand-Drilled, Old Bit, Pilot Hole	17.5	1

Table 6-3. Fatigue Test Matrix (Continued)

Specimen Type	Max Load (ksi)	Number
Machine-Drilled, Old Bit, No Pilot Hole	17.5	3
Machine-Drilled, New Bit, No Pilot Hole	17.5	3
Polished, LT	21	5
Polished, TL	21	4
Hand-Drilled, New Bit, No Pilot Hole	21	5
Hand-Drilled, New Bit, Pilot Hole	21	5
Hand-Drilled, Old Bit, No Pilot Hole	21	5
Hand-Drilled, Old Bit, Pilot Hole	21	5*
Polished, LT	25	2
Polished, TL	25	2

*Due to operator error, one specimen tested at 25 ksi.

The net section stress is calculated by the equation shown in figure 6-1, where *P* is the load, which is the remote stress multiplied by the cross-sectional area of the specimen, and the other dimensions are as shown in the figure. Using a hole diameter of 3/16 inch, or 0.1875 inch, a specimen width of 2.000 inches, and a specimen thickness of 0.0900 inch, the remote stress levels 17.5, 21, and 25 ksi correspond to net section stress levels of 19.3, 23.2, and 27.6 ksi. The figure shows that a *d*/*w* value of 0.09 from the specimen dimensions corresponds to a k_t value of approximately 2.8. Thus, the corresponding stress levels at the notch root are 54.1, 64.9, and 77.2 ksi.



d = Diameter
w = Width

Figure 6-1. Stress Concentration Calculation [25]

In addition, underload and overload tests were conducted to help correlate the results of the FASTRAN K3DL residual-stress code. Eight of these tests are shown in table 6-4. A spike underload or overload was applied to each specimen on the first cycle. The specimens were then tested at 21 ksi maximum load at $R = 0$.

Table 6-4. Underload and Overload Fatigue Test Matrix

Specimen Type	Spike Load (ksi)	Max FatigueLoad (ksi)	Number
Polished, LT, Overload	35.7	21	2
Polished, LT, Underload	-35.7	21	2
Polished, TL, Overload	35.7	21	2
Polished, TL, Underload	-35.7	21	2

6.2 EXPERIMENTAL PROCEDURE.

6.2.1 Drilling.

All hand drilling was done according to the procedure used for the hole-quality experiment, as detailed in section 4.3. The old bit was the same bit used in the previous study, and the new bit was an unused bit provided by Lockheed Martin; both were the same bit type as before. The pilot holes were 3/32 inch in diameter, also as before. The holes were not deburred prior to testing.

6.2.2 Crack Detection Gages.

Crack detection gages were successfully installed on several as-drilled and polished specimens at various loads. Micro Measurement Laboratories, Inc. type CD-23-10A gages were used, which is an isoelastic, nickel-chromium alloy laminated to a glass fiber-reinforced backing, remaining essentially linear to approximately 5000 $\mu\varepsilon$, and has a fatigue life of approximately 10 [5] cycles at 3000 $\mu\varepsilon$. The gages were attached by first applying a conditioner formula and polishing the material adjacent to the hole while being careful not to disturb any burrs. A neutralizer was then applied and any residue was removed. The gages were then mounted next to the notch root using a cyanoacrylate adhesive. Lead wires were soldered to the ends of the gage, as show in figure 6-2. A circuit was constructed to monitor the gages, as shown in figure 6-3. The circuit illuminated a light emitting diode (LED) as long as the gage remained intact. Once the gage failed, the relay switched current away from the LED and through either a siren or the test frame computer. Four of these circuits were constructed in parallel—one for each detection gage.

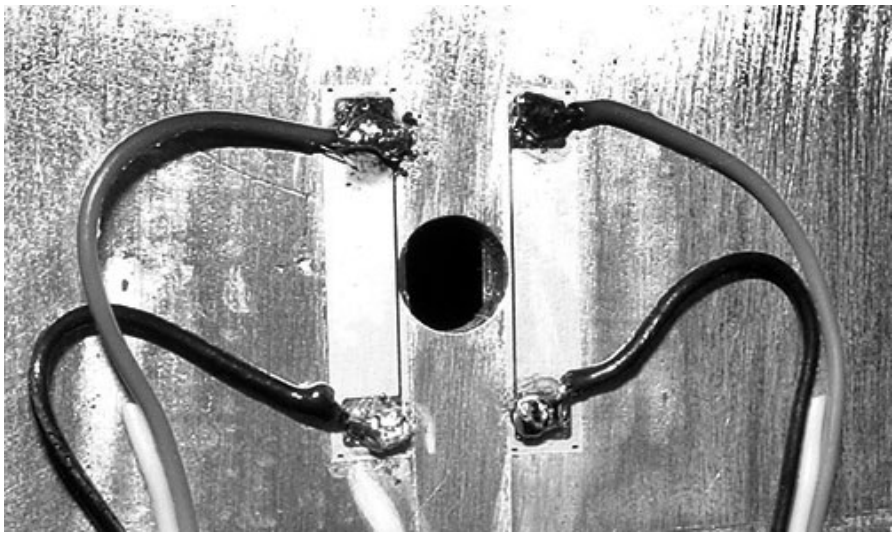


Figure 6-2. Crack Detection Gage Mounting

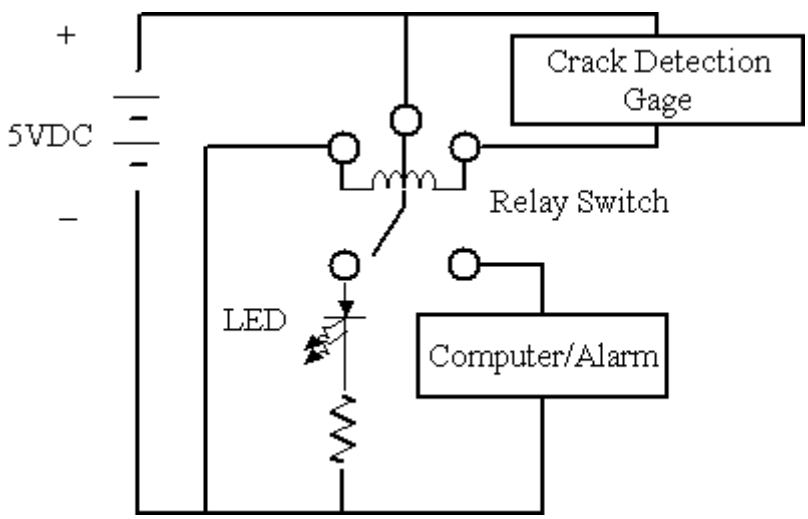


Figure 6-3. Crack Detection Circuit

6.2.3 Fatigue Testing and Data Collection.

To calculate the loading parameters, the width and thickness of each specimen were measured near each end and at the middle, and the average cross-sectional area was calculated. This area was multiplied by the maximum stress to be applied to determine the maximum load. All tests were conducted at $R = 0$ at a maximum of 10 Hz.

Specimens were tested with a 20,000 pound-force MTS® hydraulic test frame at room temperature. The specimens were mounted in hydraulic wedge grips so that $L \geq 4a$, i.e., so there was at least twice the width, or 4 inches, between grips, as shown in figure 6-4. The specimens were adjusted on the grips so the hole was at the center of the load line.

Figure 6-4. Typical Fatigue Test Setup

Cycles to failure, N_f, for the fatigue tests was the number of cycles to separation of the specimen. Cycles to initiation, N_i, was considered the number of cycles to the indication of the first crack detection gage (to the nearest 100 cycles).

The overload and underload tests used polished LT specimens. The "spike" overload was applied with a single cycle of 1.7 times the maximum tensile fatigue stress of 21 ksi, which equals 35.7 ksi. The underload was applied in a single compressive cycle of the same magnitude, or -35.7 ksi. Actions were taken to prevent buckling, as described below.

The overloaded specimens were tested in the same way as the standard specimens, except tabs were attached to the specimens to prevent breakage at the grips due to grip tooth indentations and cycles exceeding 1 million. The tabs were phenolic board attached with epoxy, as shown in figure 6-5.

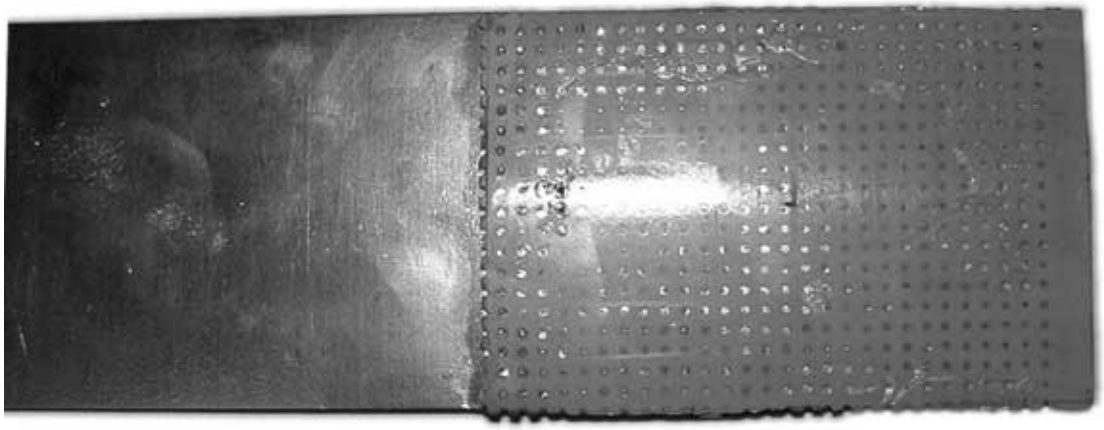


Figure 6-5. Overload Specimen With Tabs

The specimens could not support the spike underload, so two actions were taken to prevent specimen damage. The first action was to reduce the length of the specimen. Equation 6-1 was used to calculate the critical buckling length of a specimen 0.09 inch thick and 2 inches wide, where E is Young's Modulus; K is the effective-length factor, which is 0.5 for a column fixed at both ends; σ is the buckling stress, which is 35.7 ksi; I is the least moment of inertia for the cross-sectional area; and A is the cross-sectional area. Calculations showed that a maximum distance of 2.6 inches between the grips would be sufficient. The test grips were 1.75 inches long, and the minimum distance allowable between the grips during fatigue testing was 4 inches. Therefore, any specimen length below 7.5 inches would require increased gripping pressure during fatigue testing. A test on a blank specimen showed that the specimen buckled at a length of 2.2 inches between the grips. This was probably due to the slight warping of the specimen and the imperfect alignment of the grips. Cutting the specimen down to any shorter length would require gripping pressures high enough to damage the specimen and increase the likelihood of breakage at the grips.

$$L_{cr} = \frac{\pi \cdot \sqrt{E} \cdot r}{K \cdot \sqrt{\sigma}} \tag{6-1}$$

$$r = \sqrt{\frac{I}{A}} \tag{6-2}$$

To maintain an acceptable specimen length and gripping pressure, an antibuckling plate was made. The device was constructed of aluminum plate with Teflon® sheeting sandwiched between the plates and the specimen. The arrangement was fastened at the corners with washers and bolts adjusted to finger tightness, so the device could be moved across the specimen without a lot of force, as shown in figure 6-6. The specimens were then loaded with 2.2 inches between the grips, and the underloads were successfully applied.

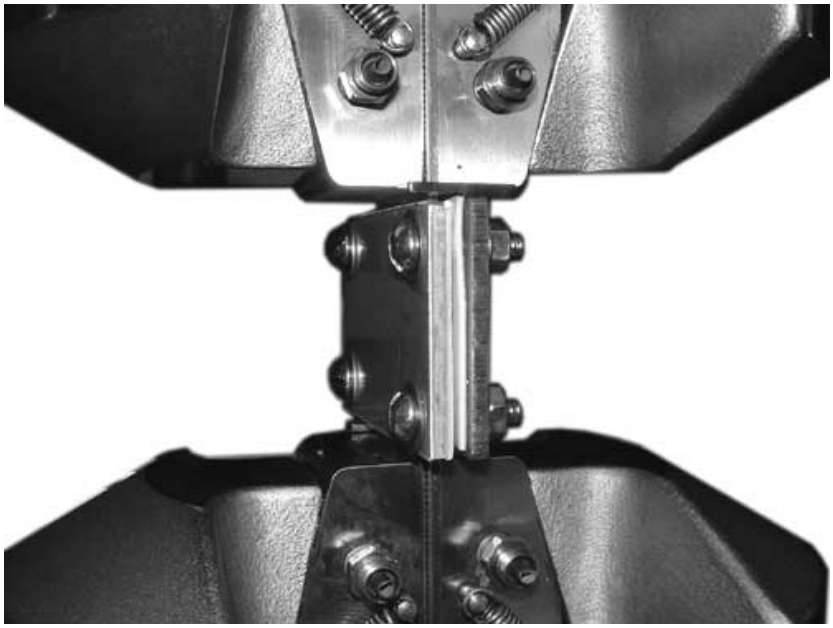


Figure 6-6. Underload Setup With Antibuckling Plates

Specimens were inspected after failure to determine the initiation site. The specimens were viewed at low power and lit from the side to reveal surface features. In the majority of specimens, a large crack formed on both sides of the hole before the specimen failed, therefore, only specimens with crack detection gages were used, and the side of the hole that first indicated a crack was examined. Crack initiation sites were determined visually and were categorized as either a corner or center crack.

6.3 DATA REDUCTION.

Fatigue is a complex phenomenon consisting of three primary stages: crack initiation, crack growth, and failure. A number of analyses were needed to sufficiently describe the nature of fatigue in this study. These analyses were performed both geometrically and statistically (as laid out in sections 4.5 and 4.6), although the statistical analyses receive the most attention in this report.

Failure was the easiest measure to define, at least in this study. It was specified as the number of cycles to separation of the specimen into two halves from a crack initiating at the hole and was designated N_f. This represents the total life of the specimen and encompasses crack initiation and growth as well as failure.

Crack growth is the stage between initiation and failure. It is defined in this study by the difference between failure and initiation, N_f - N_i. Residual stresses can retard the growth of the crack until it extends beyond the residual-stress field. To account for loading differences, the crack growth stage can also be normalized by dividing by the cycles to failure, $(N_f - N_i)/N_f$.

Crack initiation can be a difficult quantity to define. Every material contains flaws and stress concentrations before the first cycle is applied, and often, the critical crack must be identified

after failure, and a method must be employed to trace that crack back to its initial size. The crack detection gages simplified the problem in this test by defining initiation as the appearance of the first surface crack, N_{i1}. The disadvantage was that this definition was mildly dependent upon the crack initiation site, since a corner crack would be detected immediately and a center crack must grow to the surface before it would be detected. This problem makes the statistical analysis of multiple specimens necessary. The initiation can also be normalized by failure, N_i/N_f. As the first crack grew, the stress at the notch root and crack tip increased, since all tests were stress-controlled. This increase in stress eventually caused a crack to form at the notch root opposite the initial crack. The initiation of this crack was designated N_{i2}. If N_{i2} occurred shortly after N_{i1}, then the stress did not rise significantly, and the second crack was more dependent on surface features rather than on the stress increase. Therefore, $N_{i2} - N_{i1}$ was also used, as well as the normalized quantity $(N_{i2} - N_{i1})/N_f$. This quantity was also normalized by the cycles to initiation $(N_{i2} - N_{i1})/(N_f - N_{i1})$ to eliminate crack growth effects.

6.4 FATIGUE CRACK SURFACE MICROSCOPY.

To better model crack growth, it was important to specify the location and shape of the initial crack. Therefore, crack surfaces were inspected with an optical microscope. Since the most critical crack is the one that initiates first, only those specimens were inspected in which the crack detection gages successfully operated, and only on the side of the hole that cracked first.

These surfaces were digitally photographed in an optical microscope at 10-times magnification. The initiation sites were then categorized as either corner cracks or center cracks. The results were then analyzed statistically in reference to whether the specimens were polished, hand-drilled, or machine-drilled.

In addition, since the crack detection gages were not yet proven in this laboratory, the reliability of their operation was in question. In particular, it was important to know the size of a detectable crack. To determine this, the crack surface needed to be inspected while under sufficient load to open the crack, but without destroying the specimen.

Replicating tape, purchased from Ernest F. Fullam, Inc., was used for this purpose. The tape was prepared before the test by cutting a length of tape approximately 3 inches long and rolling it into a cylinder the same diameter as the hole. The test was stopped as soon as a crack was detected, the load was set to zero, and the cylinder of tape was inserted into the hole. The specimen load was then set to two-thirds of the maximum load. This load was chosen because the crack detection gages typically required at least half of the maximum load to reopen when they initially failed, indicating that the crack was completely closed at half-load. The tape was then wetted with acetate, which softened the material, and the butt end of a 5/32-inch drill bit was used to press the tape against the cracked surface, starting from the opposite side of the hole so that the cylinder would collapse upon itself. After about 1 minute, the tape was carefully peeled away from the surface and set aside, and the test was immediately resumed. Five of these replicates were made with both thin and thick replicating tape. The thin tape gave the best results and was used for microscope inspection.

The replicates were first inspected with an optical microscope. The specimens were placed on the stage and viewed at low magnification until the crack could be found. Once found, the crack

was digitally photographed at 50-times magnification and the width of the crack was measured. The clear tape proved to be problematic for this type of inspection because the crack was difficult to find and the back surface of the replicate was often confused with the front. In addition, the edges of the crack were difficult to define for measurement.

The replicates were then inspected with a scanning electron microscope (SEM). The tape was sputtered with gold to permit conductivity. The crack was readily visible under the SEM, and the edges of the crack were easy to define. The cracks were photographed at 40-times magnification to provide a global view of the entire hole surface, 200-times to illustrate the conditions at the edge of the hole, and at 1000-times to measure the width of the crack.

7. RESULTS AND DISCUSSION.

The three tests of hole quality, x-ray diffraction, and fatigue life were conducted as described in sections 4, 5, and 6, respectively. The hole-quality tests found that the pilot hole produced the greatest difference in hole quality, and the use of a pilot hole improved hole quality in every respect. The x-ray diffraction tests could not yield acceptable results due to the specimen geometry, the machining marks, and the properties of the aluminum. The fatigue tests found that drilling appears to produce compressive residual hoop stress, but hole quality predominantly determines fatigue life.

7.1 HOLE QUALITY.

Difference of means calculations were performed, as described in section 4.5, and the results are tabulated for the hand- and machine-drilled holes in tables 7-1 and 7-2, respectively. In these tables, the mean values for each factor and response combination are listed in the first two rows of each factor and response combination. The absolute values of the differences are shown in the rows entitled "Difference," and the *p*-values for the differences of means are displayed in the rows labeled "*p*-value." The standard deviations for the individual factor and response combinations are listed in the "StDev" rows. The normalized differences in means are calculated in the "Score" rows. The averages of the scores for each factor are shown in the final column, entitled "Overall Score." The raw data for the hole-quality measurements can be found in appendix A, table A-2. It should be noted that only 5 of the 24 factor and response combinations have *p*-values less than 0.1.

A statistical analysis software package called Minitab™ was used to calculate these values using the same equations given in section 4.5. The complete output created by the Minitab software package for these analyses can be found in appendix B. Minitab was also used to plot the 95% confidence intervals for each factor and response combination, some of which are shown in tables 7-1 and 7-2.

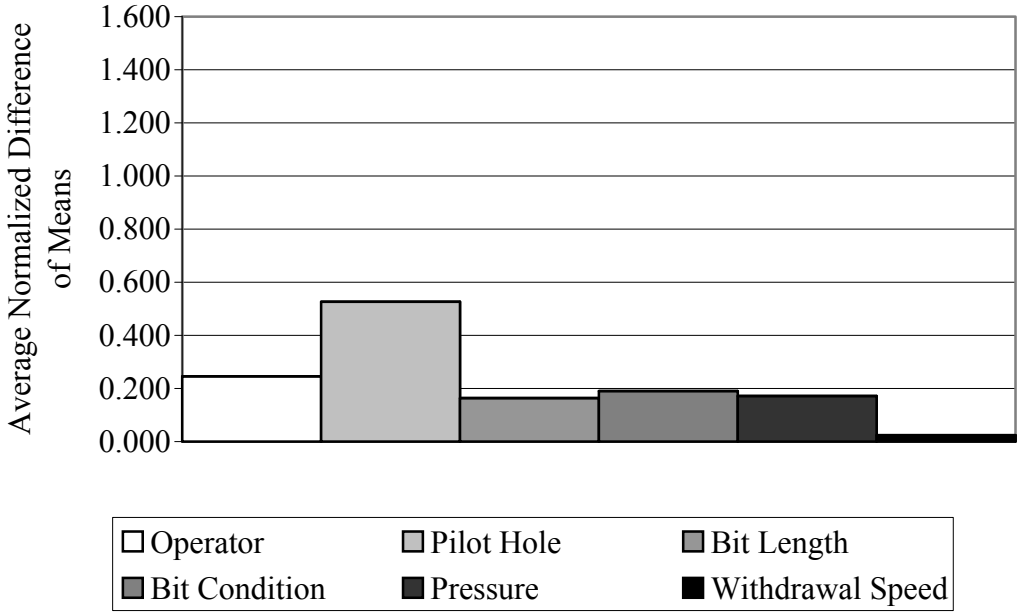
Two graphical comparisons of these results are shown in figure 7-1(a) and (b). These charts show the average normalized differences in means for each of the two tests, giving a measure of the relative significance of each factor. It is interesting to note that machine drilling resulted in more overall variability than did hand drilling.

Table 7-1. Hand-Drilled Hole-Quality Results

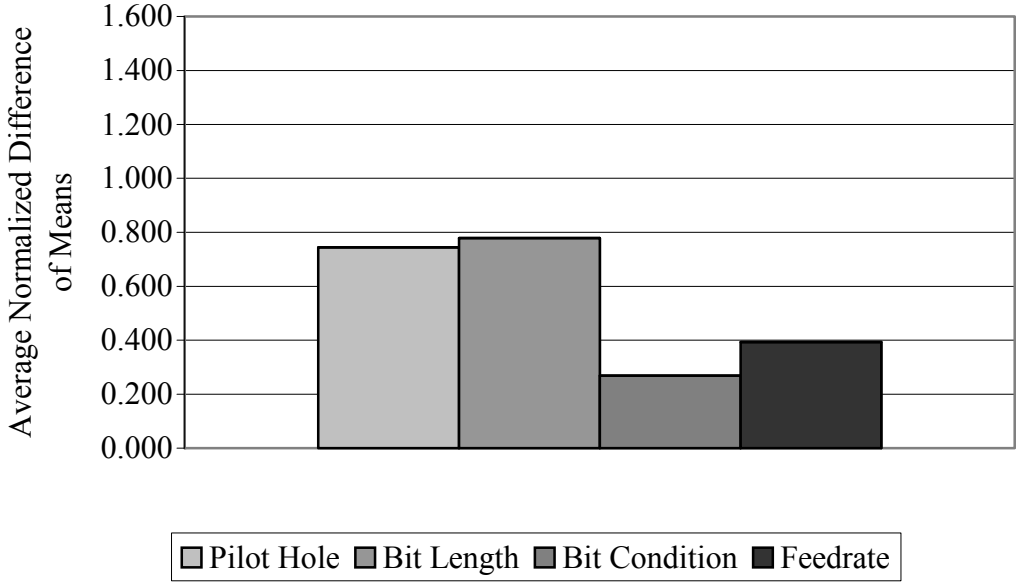
Factor	Roughness	Conicality	Gouge Angle	Gouge Number	Overall Score
Experienced	1.049	6.2	4.3	1.9	
Novice	1.051	6.3	2.8	1.1	
Difference	0.002	0.0	1.5	0.8	
p-value	0.955	0.968	0.127	0.002	
StDev	0.158	4.130	4.597	1.187	
Score	0.012	0.008	0.318	0.645	0.246
No Pilot	1.065	7.8	5.4	1.3	
Pilot Hole	1.035	4.8	1.8	1.7	
Difference	0.031	3.0	3.5	0.4	
p-value	0.341	0.000	0.000	0.159	
StDev	0.157	3.833	4.301	1.235	
Score	0.197	0.794	0.821	0.294	0.526
Long Bit	1.048	5.3	3.7	1.4	
Short Bit	1.051	7.2	3.5	1.6	
Difference	0.003	1.8	0.2	0.2	
p-value	0.926	0.030	0.827	0.509	
StDev	0.158	4.025	4.655	1.246	
Score	0.020	0.455	0.045	0.136	0.164
New Bit	1.024	5.7	3.5	1.3	
Old Bit	1.045	6.7	3.7	1.7	
Difference	0.021	1.0	0.2	0.4	
p-value	0.117	0.240	0.848	0.097	
StDev	0.155	4.099	4.655	1.230	
Score	0.133	0.244	0.040	0.346	0.191
High Press	1.044	5.6	3.0	1.4	
Low Press	1.055	6.8	4.1	1.5	
Difference	0.012	1.2	1.1	0.1	
p-value	0.720	0.157	0.264	0.679	
StDev	0.157	4.085	4.625	1.248	
Score	0.074	0.294	0.232	0.086	0.172
Full Speed	1.047	6.3	3.6	1.5	
Stopped	1.053	6.2	3.6	1.5	
Difference	0.006	0.0	0.0	0.1	
p-value	0.860	0.970	0.999	0.806	
StDev	0.158	4.130	4.656	1.248	
Score	0.037	0.008	0.000	0.051	0.024

Table 7-2. Machine-Drilled Hole-Quality Results

Factor	Roughness	Conicality	Gouge Angle	Gouge Number	Overall Score
No Pilot	1.074	3.9	6.0	1.9	
Pilot Hole	1.076	0.7	3.2	0.8	
Difference	0.003	3.2	2.9	1.2	
p-value	0.804	0.001	0.218	0.069	
StDev	0.026	2.045	5.558	1.495	
Score	0.104	1.577	0.517	0.781	0.745
Long Bit	1.089	3.2	6.5	1.7	
Short Bit	1.061	1.5	2.7	1.0	
Difference	0.028	1.7	3.7	0.7	
p-value	0.004	0.108	0.105	0.311	
StDev	0.022	2.495	5.416	1.576	
Score	1.316	0.685	0.691	0.423	0.779
New Bit	1.069	2.6	5.5	1.3	
Old Bit	1.081	2.0	3.7	1.3	
Difference	0.013	0.7	1.9	0.0	
p-value	0.240	0.546	0.427	1.000	
StDev	0.025	2.627	5.674	1.614	
Score	0.494	0.251	0.330	0.000	0.269
High Feed	1.078	1.6	4.7	1.9	
Low Feed	1.072	3.0	4.5	0.8	
Difference	0.006	1.3	0.3	1.2	
p-value	0.589	0.212	0.913	0.069	
StDev	0.026	2.555	5.756	1.495	
Score	0.224	0.525	0.045	0.781	0.394



(a)



(b)

Figure 7-1. Comparison of Overall Variability in (a) Hand Drilling and (b) Machine Drilling

7.1.1 Pilot Hole Results.

As figure 7-1(a) and (b) shows, the pilot hole produced the greatest overall variability in the hole-quality tests. This factor resulted in more than twice as much variability as the next most significant factor in the hand-drilled holes, and it scored a close second in the machine-drilled

holes. In particular, the pilot hole resulted in clearly significant mean difference in the hand-drilled tests for both conicality and gouge mark angle. In the machine-drilled holes, it yielded a significant difference in the conicality and the number of gouge marks.

The effects of the pilot hole on conicality are shown in the 95% confidence intervals in tables 7-3 and 7-4. Confidence intervals are described in section 4.6.4. It should be noted that the scales of the confidence interval plots for the two tables are different. These results clearly show that the use of a pilot hole reduces the conicality of the final hole. In fact, comparing these two tables shows that hand drilling with a pilot hole is roughly equivalent to machine drilling without a pilot hole. Thus, using a pilot hole makes hand drilling equivalent to machine drilling in the case of conicality.

Table 7-3. Effect of Pilot Hole on Conicality (Hand Drilling)

```
Factor             Mean     StDev  ------+---------+---------+---------+
No Pilot Hole     7.800     4.768                       (------*------)
Pilot Hole        4.758     2.646  (-------*------)
                                   ------+---------+---------+---------+
p-value = 0.000                         4.5       6.0       7.5       9.0
```

Table 7-4. Effect of Pilot Hole on Conicality (Machine Drilling)

```
Factor             Mean     StDev  ----+---------+---------+---------+--
No Pilot Hole     3.925     2.798                       (-------*------)
Pilot Hole        0.700     0.732   (------*-------)
                                   ----+---------+---------+---------+--
p-value = 0.001                       0.0       1.6       3.2       4.8
```

This effect of the pilot hole on conicality is likely due to three factors: the quick biting of the bit into the workpiece, the increased forward speed of the bit, and the guiding effect of the pilot hole. When the drilling begins, the pilot hole provides a definite starting location for the bit so it can instantly bite into the edges of the hole. Without a pilot hole, the bit can wander across the surface before anchoring, sometimes in the wrong location. Not only does the cutting start more quickly with a pilot hole, but it also proceeds more quickly because less material must be removed, reducing bit wobbliness at the beginning of the drilling when the bit is least constrained. Once the bit enters the workpiece, the pilot hole guides the bit throughout the remainder of the drilling, providing it with a predetermined path. In the case of machine drilling, the drill press constrains the end of the bit, reducing the amount that the tip can wander from its path, which produces less conicality than hand drilling. However, the pilot hole significantly improves conicality even when the hole is drilled by machine.

The gouge mark angle was also significantly affected by the use of the pilot hole, reducing the angle in hand drilling, as shown in table 7-5. An interesting insight into the cause of gouging can be made from these results. The angle of the gouge marks was originally thought to be directly related to the forward speed of the bit, so a higher speed would produce a higher angle. However, the use of a pilot hole increases the forward speed in hand drilling since less material has to be removed, but it reduces the angle of the gouge marks, suggesting that the forward speed of the drill does not affect the gouge mark angle. This is confirmed by the result of the machine-

drilling feed rate in table 7-6, which shows essentially no difference on the gouge mark angle even though the speed of drilling was increased threefold.

Table 7-5. Effect of Pilot Hole on Gouge Angle (Hand Drilling)

```
Factor              Mean     StDev  -------+---------+---------+---------
No Pilot Hole      5.378     5.849                    (-----*-----)
Pilot Hole         1.848     1.857  (-----*-----)
                                    -------+---------+---------+---------
p-value = 0.000                           2.0       4.0       6.0
```

Table 7-6. Effect of Feed Rate on Gouge Angle (Machine Drilling)

```
Factor              Mean     StDev  -----+---------+---------+---------+-
High               4.725     4.598   (-----------------*----------------)
Low                4.467     6.717  (----------------*-----------------)
                                    -----+---------+---------+---------+-
p-value = 0.913                         2.0       4.0       6.0       8.0
```

The use of a pilot hole also reduced the number of gouge marks. This was evident in machine drilling, where there were more than twice as many gouge marks on average in the holes drilled without a pilot hole than those drilled with the pilot hole, as shown in table 7-7. The combined results of the number of gouge marks and angle of gouge marks show that the formation of these marks is highly dependent on the use of the pilot hole, suggesting that the formation of gouges is dependent upon the orientation of the bit in relation to the workpiece, rather than the speed or quality of the drill bit.

Table 7-7. Effect of Pilot Hole on Gouge Number (Machine Drilling)

```
Factor              Mean     StDev  --+---------+---------+---------+----
No Pilot Hole      1.917     1.730                 (----------*----------)
Pilot Hole         0.750     1.215  (----------*-----------)
                                    --+---------+---------+---------+----
p-value = 0.069                      0.00      0.80      1.60      2.40
```

7.1.2 Bit Length Results.

The bit length produced a great amount of variability in machine drilling, as shown in figure 7-1(b), and is approximately equal to the effect produced by the pilot hole. In hand drilling, however, the next four most significant factors after the pilot hole are approximately equal and much less significant, as shown in figure 7-1(a). The greatest variability due to bit length is found in surface roughness—the only factor that significantly affected roughness in either of the two tests. The bit length also significantly affected conicality in both hand drilling and machine drilling. It caused approximately equal variability in the gouge mark angle and conicality in machine drilling.

The large surface-roughness effect in machine drilling is confirmed in table 7-8, showing that longer bits increased surface roughness—probably due to “chatter” of the bit, which, audibly, was very apparent during drilling. The difference in surface quality was also visibly very apparent, as shown in figure 7-2(a) and (b), which shows the characteristic rippled surface

caused by chattering. This effect does not appear in hand drilling because the shank end of the bit is held in place by the operator, so any bucking of the bit is absorbed by the operator's hand. In machine drilling, however, the shank end of the bit is firmly constrained by the massive drill press so vibrations are absorbed by the workpiece. The longer the drill bit, the more it can deflect, increasing chatter and, therefore, surface roughness.

Table 7-8. Effect of Bit Length on Surface Roughness (Machine Drilling)

```
Factor            Mean     StDev  --+---------+---------+---------+----
Long Bit         1.0891    0.0263                     (--------*--------)
Short Bit        1.0608    0.0152   (-------*--------)
                                  --+---------+---------+---------+----
p-value = 0.004                    1.050     1.065     1.080     1.095
```

(a)

(b)

Figure 7-2. Bore of a Hole Drilled With a (a) Long Bit and (b) Short Bit

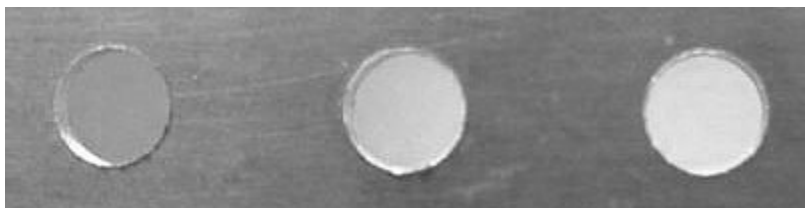
Conicality was affected by the bit length in both hand drilling and machine drilling, although in opposite ways. A longer bit produced less conicality in hand drilling, as shown in table 7-9, and greater conicality in machine drilling, as shown in table 7-10. This can be explained in part by the different ways that the bit is more constrained, as discussed in the previous paragraph. In hand drilling with a long bit, the point of the bit is constrained and gives the operator more control over the angle of the bit, because the operator can see and feel the orientation of the drill to the workpiece more accurately. Additionally, as the length of the bit increases, any straying of the hand produces a smaller angle relative to the workpiece. Conversely, in machine drilling, the shank end of the bit is constrained, and a longer bit allows the point of the bit to deflect more, cutting into the material around the entrance of the hole. In fact, the longer bits used in this experiment tended to produce slightly triangular hole bores, as shown in figure 7-3(a) and (b), giving evidence of increased deflection of the bit.

Table 7-9. Effect of Bit Length on Conicality (Hand Drilling)

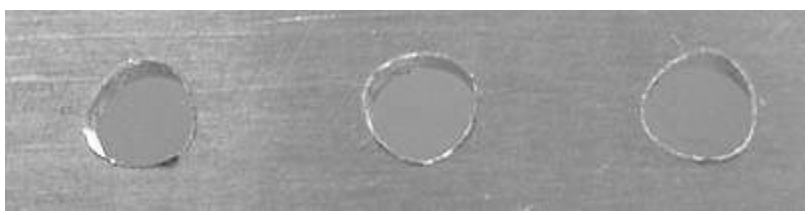
```
Factor              Mean     StDev  ------+---------+---------+---------+
Long Bit           5.332     2.863   (--------*---------)
Short Bit          7.162     4.920                  (---------*--------)
                                    ------+---------+---------+---------+
p-value = 0.030                          4.8       6.0       7.2       8.4
```

Table 7-10. Effect of Bit Length on Conicality (Machine Drilling)

```
Factor              Mean     StDev  -+---------+---------+---------+-----
Long Bit           3.167     3.355             (---------*---------)
Short Bit          1.458     1.091   (---------*---------)
                                    -+---------+---------+---------+-----
p-value = 0.108                     0.0       1.5       3.0       4.5
```



(a)



(b)

Figure 7-3. (a) Round and (b) Triangular Holes

The gouge mark angle was affected by bit length in machine drilling. In this study, the bit length was the only factor that significantly affected the gouge mark angle in machine drilling (the pilot hole, as discussed in section 7.1.1, is the only factor of the six identified that significantly affects this angle in hand drilling). As shown in table 7-11, the long bit produced a steeper gouge mark angle.

Table 7-11. Effect of Bit Length on Gouge Mark Angle (Machine Drilling)

```
Factor              Mean     StDev  --+---------+---------+---------+----
Long Bit           6.467     6.270              (----------*---------)
Short Bit          2.725     4.399  (----------*----------)
                                    --+---------+---------+---------+----
p-value = 0.105                      0.0       3.0       6.0       9.0
```

In addition, the analysis of variances revealed that the bit length interacted with the pilot-hole factor in hand drilling to affect conicality. Figure 7-4 shows that the conicality of the holes was not affected when drilled with a long bit, but was strongly affected by the pilot hole when drilled

with a short bit. Not surprisingly, the pilot hole reduced the conicality of the holes in the case of the short bit. This was probably due to the operator having less control with a shorter bit.

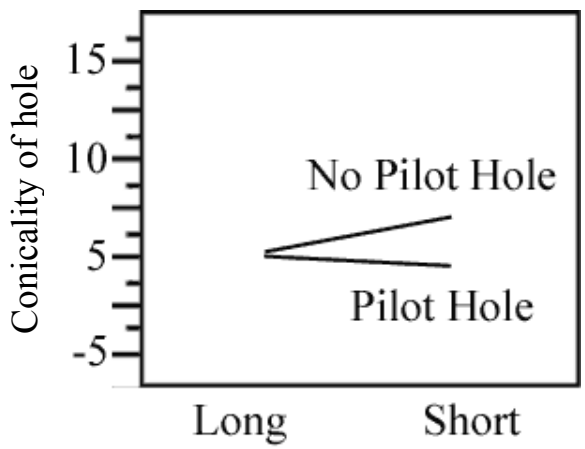


Figure 7-4. Interaction of the Bit-Length and Pilot-Hole Factors

7.1.3 Bit Condition Results.

The condition of the bit, along with pressure or feed rate, produced moderate hole-quality variability in both hand drilling and machine drilling. It was thought that a duller drill bit would produce more plastic deformation and, therefore, higher residual compressive hoop stress in drilling than would a sharp bit. However, residual stresses are not visible to the eye, and it was not thought that the bit condition would greatly affect hole quality. The mechanics commented on the longer drilling time required for an old bit. The only hole-quality metric that was significantly affected by bit condition was the number of gouge marks in hand drilling.

Table 7-12 shows the confidence intervals for bit condition on the number of gouge marks and shows that the new bit produced fewer gouge marks than the old bit. This is most likely due to the same effect that caused the reduction in the number of gouge marks due to the use of a pilot hole, since the new bit drills more quickly through the workpiece.

Table 7-12. Effect of Bit Condition on Gouge Mark Number (Hand Drilling)

```
Factor              Mean     StDev  ----+---------+---------+---------+--
New Bit            1.277     1.057  (---------*----------)
Old Bit            1.702     1.382             (----------*---------)
                                    ----+---------+---------+---------+--
p-value = 0.097                        1.05      1.40      1.75      2.10
```

7.1.4 Pressure or Feed Rate Results.

The overall hole-quality variability of the feed-rate factor in machine drilling is due primarily to the number of gouge marks. Table 7-13 gives the factor confidence intervals, showing that high feed rate produced more gouge marks than a low feed rate. Although the bit does cut through the workpiece more quickly with a high feed rate, it is forced to do so, in contrast to the effect of the

new bit, which allows the bit to cut through the workpiece more easily. The higher applied pressure likely causes more deflection of the point of the bit, gouging the surface more often. This effect is not replicated in hand drilling, probably due to the lower maximum pressure that can be applied by an operator compared to a machine.

Table 7-13. Effect of Feed Rate on Gouge Mark Number (Machine Drilling)

```
Factor              Mean     StDev  --+---------+---------+---------+----
High Feed Rate     1.917     1.730                (----------*----------)
Low Feed Rate      0.750     1.215  (----------*-----------)
                                    --+---------+---------+---------+----
p-value = 0.069                      0.00      0.80      1.60      2.40
```

7.1.5 Operator Experience Results.

In hand drilling, operator experience produced the second greatest amount of overall variability, due primarily to gouging effects. This factor was not included in machine drilling since machine drilling by definition removes this human factor. Most of the overall variability produced by the operator factor is attributed to the number of gouge marks, as this was the only response with a *p*-value below 0.1, as shown in table 7-14. Surprisingly, the experienced operator produced more gouge marks (about 2 per hole) than did the novice (about 1). Operator experience also produced a marginal effect on the gouge mark angle, but the scatter is too large to make any conclusions.

Table 7-14. Effect of Operator Experience on the Number of Gouge Marks

```
Factor              Mean     StDev  -+---------+---------+---------+-----
Experienced        1.872     1.361                    (--------*-------)
Novice             1.106     0.983  (--------*-------)
                                    -+---------+---------+---------+-----
p-value = 0.002                     0.80      1.20      1.60      2.00
```

7.1.6 Withdrawal Speed Results.

No measurable effect was produced by the withdrawal-speed factor in hand drilling. This factor was not included in the machine-drilling matrix because the drill rotation is always kept at full speed in machine operations. Especially surprising is the fact that there was no difference in the angle of the gouge marks, since it was thought that stopping the bit would deeply score the surface of the hole at a 90-degree angle. This is further evidence that gouging is a factor of the orientation of the bit to the workpiece, rather than a factor of the drill or bit parameters.

Thus, the pilot-hole factor results in the largest change in hole quality, and the use of a pilot hole generally improves hole quality. The bit length stands out in machine drilling, where a long bit significantly roughens the surface. Otherwise, the bit length produced little hole-quality difference, roughly equivalent to that made by the bit condition, pressure or feed rate, and the operator. The speed of the bit upon withdrawal made no significant difference in hole quality.

7.1.7 Burr Types.

Section 4.5.1 discussed the three types of burrs (curling, triangular, and bulge) observed in the sectioned holes. As detailed in the procedure, burr geometries were recorded for each sectioned hole. The data shows that the curling burr is dependent on the operator and pilot-hole factors; the triangular burr is only dependent on the use of a pilot hole; and the bulge burr is dependent on the pilot hole, pressure, and operator.

The curling burr is most dependent on the operator, with a *p*-value of 0.000. Table 7-15 shows that machine drilling was the factor most likely to result in a curling burr. The average number of curling burrs observed in machine-drilled holes was 0.96. Since a maximum of two exit burrs could be observed for each hole, machine drilling was 48% likely to create a curling burr. The curling burr also appears to be operator dependent.

Table 7-15. Effect of Operator on Curling Burr

```
Factor              Mean     StDev  ---+---------+---------+---------+---
Experiened        0.4792    0.7143            (---*---)
Machine           0.9583    0.7506                      (-----*-----)
Novice            0.0638    0.2471  (----*---)
                                    ---+---------+---------+---------+---
p-value = 0.000                       0.00      0.40      0.80      1.20
```

Table 7-16 shows that a curling burr is also much more likely to be formed when a pilot hole is not used, with a *p*-value of 0.034. Approximately 27% of the holes drilled without a pilot hole resulted in a curling burr, while approximately 14% of those drilled with a pilot hole showed curling burrs.

Table 7-16. Effect of Pilot Hole on Curling Burr

```
Factor              Mean     StDev  -----+---------+---------+---------+-
No Pilot Hole     0.5424    0.6778                (-------*--------)
Pilot Hole        0.2833    0.6402   (-------*--------)
                                    -----+---------+---------+---------+-
p-value = 0.034                         0.20      0.40      0.60      0.80
```

The triangular burr showed a strong correlation to the use of a pilot hole, with a *p*-value of 0.000, as shown in table 7-17. As with the curling burr, the triangular burr is more likely to form when a pilot hole is not used, which suggests that the two burrs are related to each other. About 53% of the holes drilled without a pilot hole formed a triangular burr, while only about 14% of those drilled with a pilot hole formed a triangular burr. The combined probability of a triangular and curling burr resulting from the use of a pilot hole is about 80%, which is the strongest correlation in this study. This correlation, along with the similar shapes of the burrs, suggests that the curling burr is a precursor to the triangular burr, while the bulge burr is based on a separate phenomenon.

Table 7-17. Effect of Pilot Hole on Triangular Burr

```
Factor             Mean     StDev  -------+---------+---------+---------
No Pilot Hole    1.0508    0.7526                            (-----*-----)
Pilot Hole       0.2833    0.5552   (----*-----)
                                   -------+---------+---------+---------
p-value = 0.000                          0.30      0.60      0.90
```

The use of a pilot hole also affected the formation of the bulge burr, but in this case, a bulge burr was more likely to form when a pilot hole was used, with a *p*-value of 0.000. Approximately 32% of the holes drilled with a pilot hole formed a bulge burr, while only about 8% of those drilled without a pilot hole formed a bulge burr, as shown in table 7-18.

Table 7-18. Effect of Pilot Hole on Bulge Burr

```
Factor             Mean     StDev  ----------+---------+---------+------
No Pilot Hole    0.1695    0.3784  (------*------)
Pilot Hole       0.6333    0.8431                     (-----*------)
                                   ----------+---------+---------+------
p-value = 0.000                            0.25      0.50      0.75
```

The pressure applied to the drill appears to contribute to the formation of the bulge burr, with a *p*-value of 0.014. High pressure is about 28% likely to produce a bulge burr, whereas low pressure resulted in bulge burrs in less than 13% of the holes. These results are displayed in table 7-19. The shape of the bulge burr suggests that it results from a large deformation in the axial direction of the material surrounding the hole. The pressure results clearly agree with this hypothesis. The pilot hole results may also substantiate this hypothesis, since a pilot hole would allow the bit to proceed through the hole by its own twisting action, rather than being pushed through.

Table 7-19. Effect of Pressure on Bulge Burr

```
Factor             Mean     StDev  -------+---------+---------+---------
High Pressure    0.5593    0.7938                  (--------*--------)
Low Pressure     0.2500    0.5407   (-------*--------)
                                   -------+---------+---------+---------
p-value = 0.014                  0.20      0.40      0.60
```

Hand drilling also appears more likely to result in a bulge burr, with a *p*-value of 0.020. About 24% of the holes drilled by hand resulted in a bulge burr, while only about 4% of the machine-drilled holes resulted in such a burr, as shown in table 7-20.

Table 7-20. Effect of Operator vs Bulge Burr

```
Factor             Mean     StDev  -------+---------+---------+---------
Experienced      0.5625    0.7964                     (------*-----)
Machine          0.0833    0.2823   (--------*--------)
Novice           0.4043    0.6808                (-----*------)
                                   -------+---------+---------+---------
p-value = 0.020                          0.00      0.30      0.60
```

Thus, the curling burr and triangular burr appear to be directly related to each other, such that the curling burr is a precursor to the triangular burr. These burrs may be the result of both local deformation of residual exit face material and plastic flow within the bore of the hole. The bulge burr appears to be related to the amount of axial deformation of the material surrounding the hole.

7.2 X-RAY DIFFRACTION.

The material and specimen geometry proved too problematic to obtain consistent residual stress results using x-ray diffraction. These problems persisted despite trying a large variety of testing parameters. The problems were attributed to the material properties, curvature of the hole, and roughness of the drilled surface.

After testing a number of different specimens, only one specimen was tested until consistent results could be obtained. A hole that had been machine drilled using an old bit, which had a very smooth surface relative to the other holes, was chosen because it would minimize roughness effects and have a high chance of containing a residual hoop stress field. A variety of different optics and beam sizes were tried before the wide and narrow geometry discussed in section 5.3 was used. The narrowness of the beam minimized the effect of the curvature of the hole surface, and the width of the beam maintained sufficient beam intensity while still ensuring that the beam was only incident on the specimen and not on the aluminum stage. A scan was run without a specimen and compared to the results of a scan run with a specimen that had the same parameters to ensure that the inconsistencies were not due to readings from the stage.

When all the parameters were optimized, three scans were run on the same specimen on three different days using the same procedure. The resultant graphs of $\sin^2\Psi$ versus d are shown in figures 7-5 through 7-7. All the graphs have significant scatter, although two of the three have almost equal slopes, suggesting residual hoop stress. A composite of these three graphs is shown in figure 7-8, which shows that the two graphs with similar slopes have widely different average d-spacings, while two of the graphs with differing slopes have very similar d-spacings. This amount of variability among scans would prevent meaningful comparison between specimens.

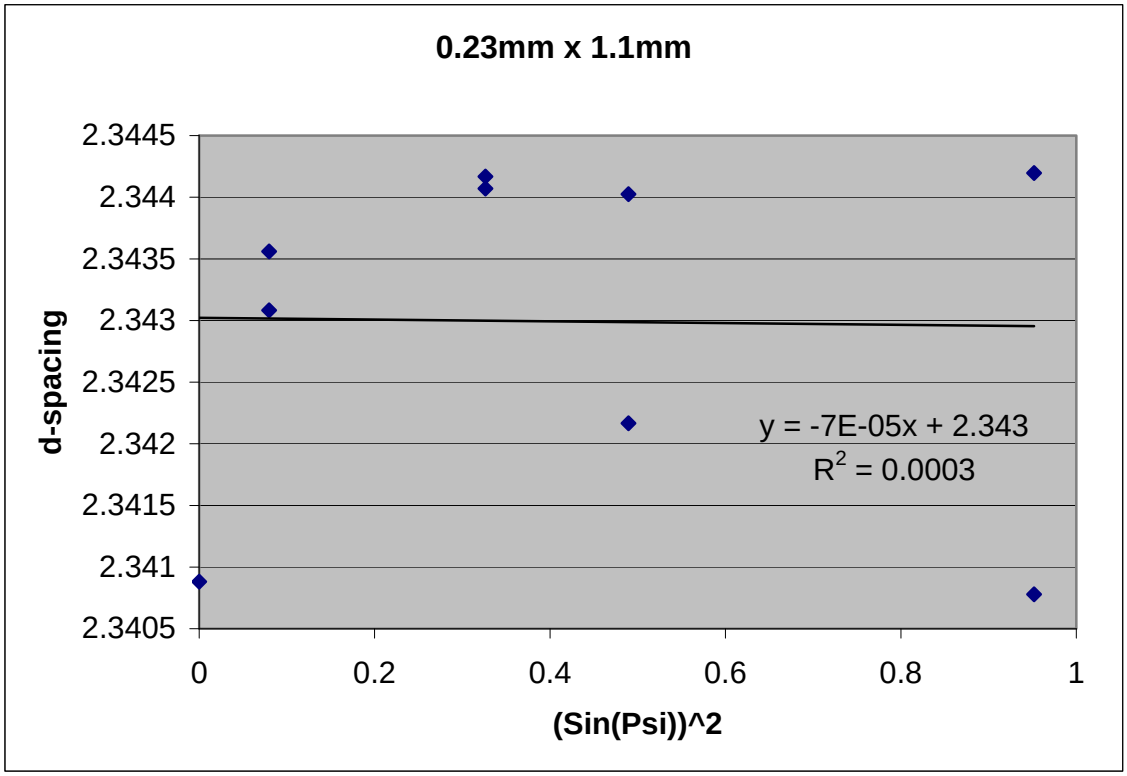


Figure 7-5. First X-Ray Scan of Specimen A89N8-10

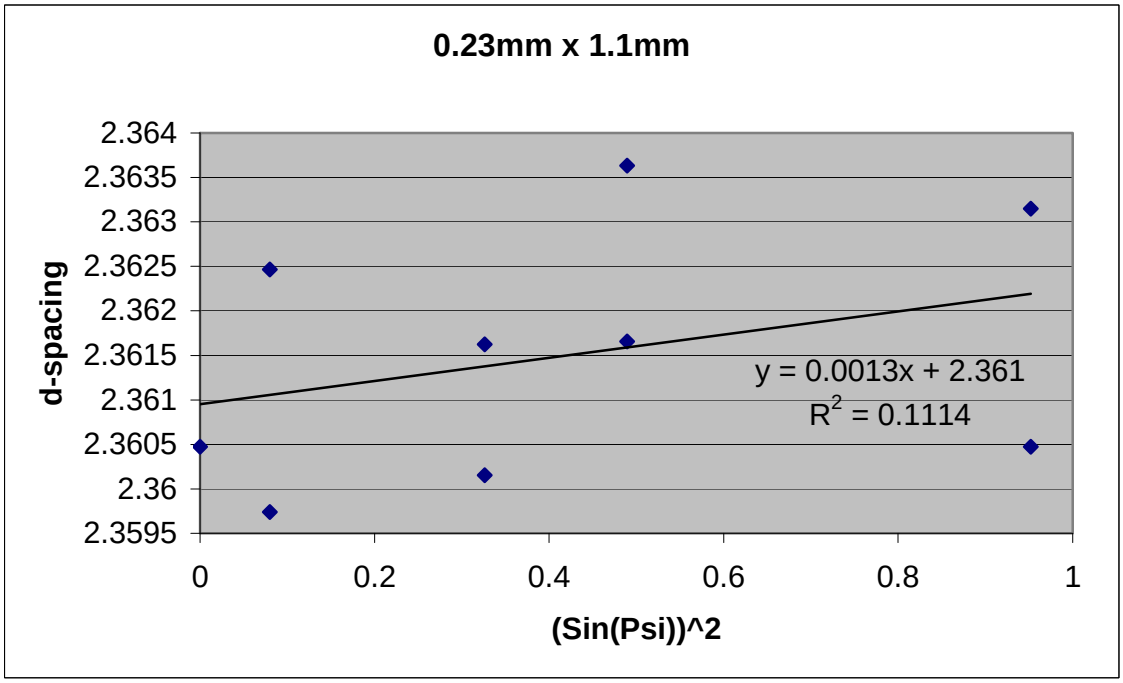


Figure 7-6. Second X-Ray Scan of Specimen A89N8-10

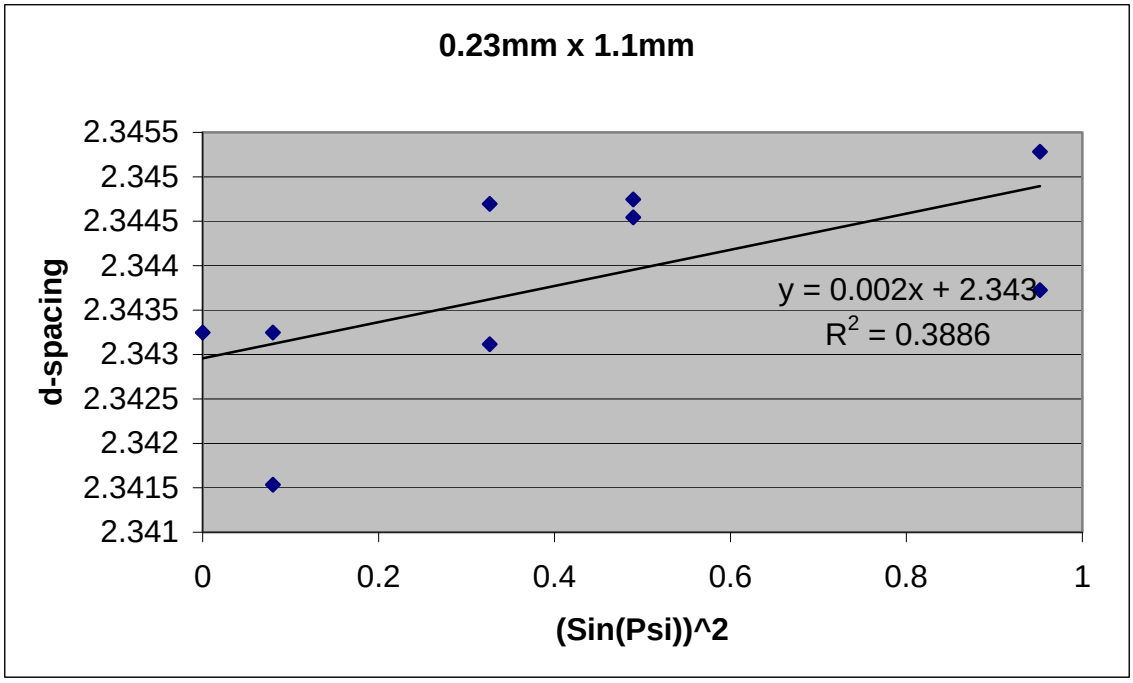


Figure 7-7. Third X-Ray Scan of Specimen A89N8-10

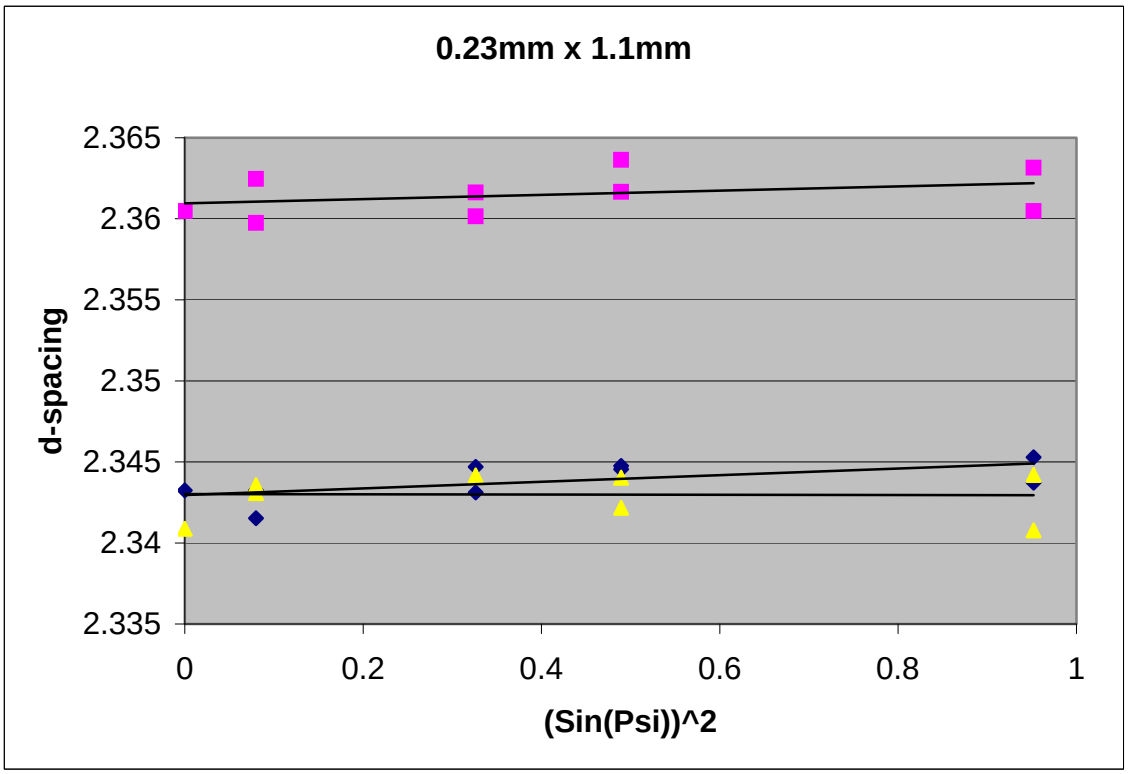


Figure 7-8. Composite of Three X-Ray Scans of Specimen A89N8-10

These inconsistencies can be attributed to three factors: material properties, curvature of the hole, and roughness of the drilled surface. Two material property concerns are the depth of x-ray penetration and specimen texture. The low relative density of aluminum allows x-ray to penetrate several hundred microns into the surface. The residual stresses induced by drilling are only on the order of about 20 microns. Since x-ray diffraction averages over the depth of penetration, the effect of the residual stresses will be greatly reduced. Specimen texture refers to the quality of the material grains. Since the batch of aluminum provided for this study was rolled, its grains are highly textured. This texturing can produce a large amount of scatter in x-ray diffraction results. X-ray diffraction also produces the best results on flat surfaces. The curvature of the hole bore causes the beam to strike the specimen at different angles, causing additional scatter. In addition, the curvature may cause the beam to strike the specimen at unpredictable angles since the specimen is tilted, and may cause a large amount of scatter if the specimen is rotated as much as a few microns off-axis. Although using a narrow beam minimized this effect, it cannot be completely eliminated. Finally, the surface of the hole is invariably roughened to some degree by machining marks. The curvature of the specimen and the roughness of the surface cause beam scatter. This could be reduced by chemically polishing the specimens, but the polishing would also eliminate the greatest residual stresses—those nearest to the surface.

The overall effect was probably the result of a combination of these factors, two of which were minimized by the geometry of the beam and the choice of a smooth specimen. Regardless, the variability of the scans remained too great to permit meaningful comparisons between specimens. Therefore, x-ray diffraction had to be eliminated as a method of determining relative residual stresses.

7.3 FATIGUE TESTING.

Fatigue tests were conducted at three stress levels corresponding to three conditions relative to the yield stress of the material at the notch root: 17.5 ksi, which is well below the yield stress; 21 ksi, just below the yield stress; and 25 ksi, well above the yield stress. Since the pilot hole was the most significant factor affecting hole quality and the bit condition was believed to most significantly affect the magnitude of residual stresses, these two factors were chosen for the initial tests. Chemically polished specimens were used as a baseline. Additional polished specimens were later used to provide more data at the 17.5 ksi level. A set of specimens was also machine drilled, three with an old bit and three with a new bit, for testing at 17.5 ksi. Both drill bits were short bits, and all six specimens used a pilot hole and low feed rate.

The cycles to failure for the various tests are shown in figure 7-9, where failure was considered specimen separation. These results show that the polished specimens lasted much longer than the as-drilled specimens. This difference is attributed primarily to machining marks, which provide stress concentrations. Within the sets of as-drilled specimens, results indicate that the dull bit did induce residual compressive hoop stresses, increasing fatigue life of the fastener holes.

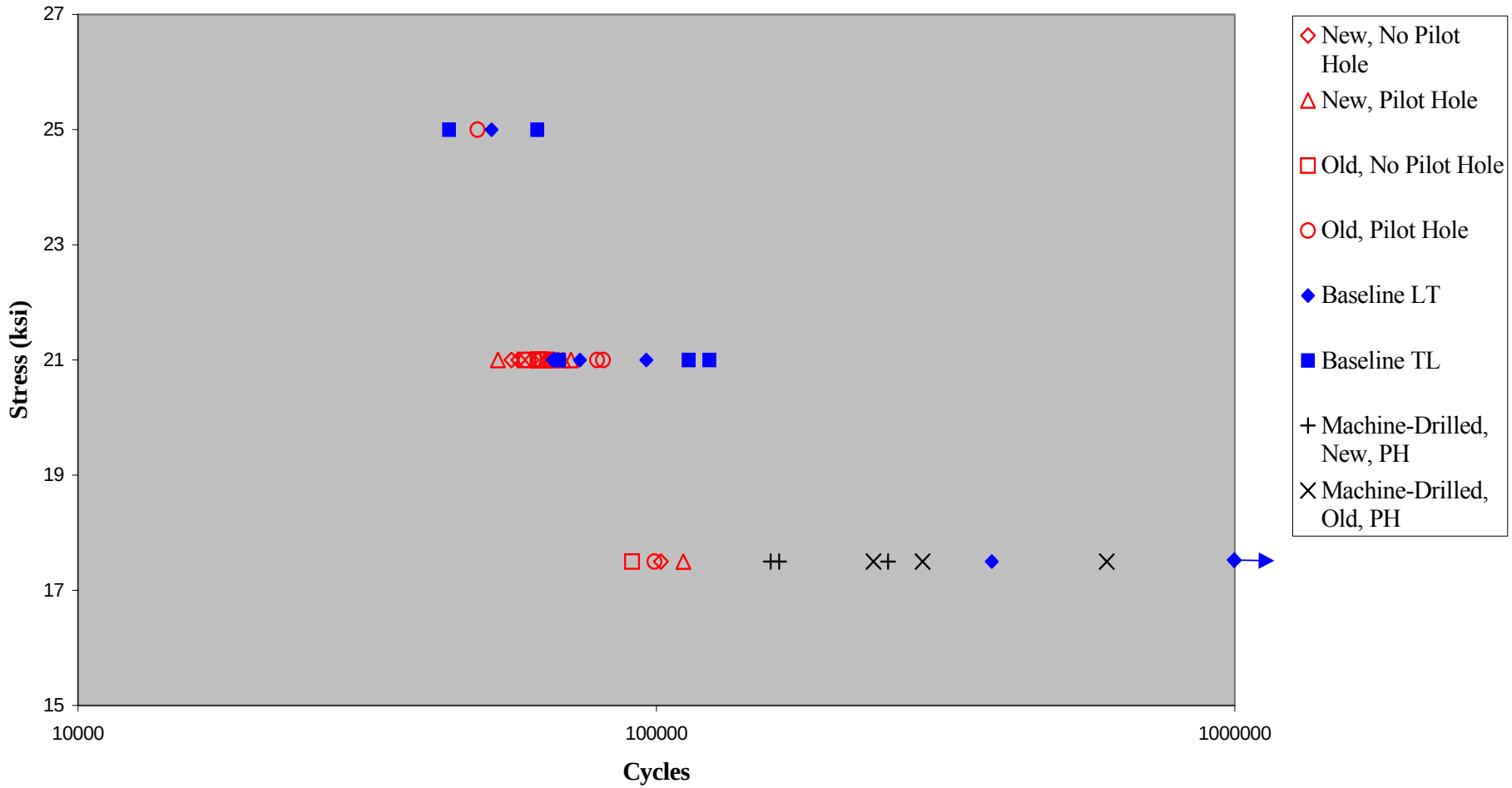


Figure 7-9. Fatigue Test Cycles to Failure

7.3.1 Testing at 21 ksi.

The primary fatigue tests were conducted at 21 ksi, which is just below the yield stress of the material at the notch root. Any residual stresses in a polished specimen would effectively reduce the applied stress to a level below the yield stress and retard crack initiation and early crack growth. The tests included five specimens each of the as-drilled combinations of new bit, no pilot hole; new bit, pilot hole; old bit, no pilot hole; and four of the old bit, pilot hole specimens (one was tested at 25 ksi due to operator error). Three polished specimens each in the LT and TL directions, which were assumed to be without residual stresses, were tested at this level to provide a baseline. Additionally, four underloaded and four overloaded specimens (two each in the TL and LT directions) were tested to be used for correlation with FASTRAN predictions.

A comparison of the cycles to failure of the polished LT specimens and the 24 as-drilled specimens is shown in table 7-21. The fatigue life of the as-drilled specimens is clearly reduced, despite the large standard deviation of the polished specimens, because there were only two polished LT specimens tested. The reduction in fatigue life appears to be about 20%, although more polished specimens would need to be tested to reduce the standard deviation. The difference is most likely due to hole quality, in particular the gouge marks, since even one of these large stress concentrations would provide a large enough stress concentration to quickly initiate a crack.

Table 7-21. As-Drilled vs Polished LT Cycles to Failure (21 ksi)

```
Factor             Mean     StDev  --+---------+---------+---------+----
Polished          91438     28532                (--------*--------)
Hand Drilled      64484      6989   (---*---)
                                    --+---------+---------+---------+----
p-value = 0.001                     60000     75000     90000    105000
```

In light of this apparent hole-quality effect, a closer look at the fatigue life of the as-drilled holes was warranted. The difference in fatigue lives was found to be due to crack initiation. Table 7-22 shows the holes drilled with the old bit lasted longer than those drilled with the new bit, while the pilot hole had little effect on fatigue life. In fact, the analysis of variance of cycles to initiation for the pilot-hole factor resulted in a *p*-value of only 0.401, while the bit condition resulted in a *p*-value of 0.011, as shown in table 7-23. These two tables show that the old bit resulted in a longer life than the new bit. It should be recalled that the old bit produced significantly more gouge marks and a marginally greater surface roughness, while having no significant effect on conicality or gouge mark angle. Thus, this longer fatigue life produced by the old bit contrasted with its poorer hole quality, suggests that the old bit does indeed produce higher compressive residual stresses. The fact that the holes drilled with the old bit took about 40% longer to initiate a crack proves that this effect is not insignificant.

Table 7-22. N_i for As-Drilled Holes (21 ksi)

```
Factor              Mean     StDev  ---------+---------+---------+-------
New Bit, No Pilot  37700      8227  (---------*---------)
New Bit, Pilot     39575      9871     (--------*--------)
Old Bit, No Pilot  48333      9500           (---------*---------)
Old Bit, Pilot     57550      9088                    (--------*--------)
                                    ---------+---------+---------+-------
p-value = 0.054                            36000     48000     60000
```

Table 7-23. Bit Condition vs N_i (21 ksi)

```
Factor              Mean     StDev  ---------+---------+---------+-------
New Bit            38771      8502  (-------*------)
Old Bit            53600      9780                 (-------*------)
                                    ---------+---------+---------+-------
p-value = 0.011                            40000     50000     60000
```

After the first crack initiated, an interesting phenomenon took place to equalize the fatigue lives. Table 7-24 shows that the cycles from initiation to failure are higher for the new bit than for the old bit, reversing the above trends. The most probable reason for this is that multiple cracks are forming simultaneously in the holes drilled with the old bit, because of the higher number of gouge marks, whereas cracks tend to form more in a series in the holes drilled with a new bit. Table 7-25 shows the confidence intervals for the normalized difference between the cycles to initiation of the first surface crack and initiation of a surface crack on the opposite side of the hole. This theory appears plausible, but the *p*-value of 0.131 provides only marginal confidence, due primarily to the low number of initiation data points in these tests.

Table 7-24. Bit Condition vs N_f-N_i (21 ksi)

```
Factor              Mean     StDev  ----------+---------+---------+------
New Bit            23021      7465                  (---------*---------)
Old Bit            15341      3282  (----------*---------)
                                    ----------+---------+---------+------
p-value = 0.040                             15000     20000     25000
```

Table 7-25. Bit Condition vs $(N_{i2}-N_{i1})/N_f$ (21 ksi)

```
Factor              Mean     StDev  -+---------+---------+---------+-----
New Bit           0.1921    0.1210               (----------*----------)
Old Bit           0.0946    0.0602  (------------*-----------)
                                    -+---------+---------+---------+-----
p-value = 0.131                     0.000     0.080     0.160     0.240
```

The combined effect of the two competing trends of crack initiation and growth, shown in tables 7-24 and 7-25, approximately equalize the as-drilled hole fatigue lives. It is important to remember that the overall differences in cycles to failure for the as-drilled specimens are small in comparison to those of the polished specimens, as shown in table 7-21 and figure 7-8. So, while residual stresses do appear to be a factor, they are offset by the detrimental effects of machining marks. This may be a mixed blessing when it comes to aircraft production, for although the residual stresses do not provide a great improvement in fatigue life, they do appear to reduce the

effects of machining marks, and essentially equalize the variables involved in the manufacturing process.

7.3.2 Testing at 17.5 ksi.

As shown in figure 7-8, the as-drilled specimens had much shorter fatigue lives than the polished specimens, as predicted from the 21-ksi test results. All the polished specimens were runouts to three million cycles except for one, which initiated a crack on one side and fractured before initiating a crack on the opposite side, suggesting that either the hole was drilled off-center or there was a flaw at the notch root. These results confirm that machining marks play a larger role in fatigue life than residual stress.

Figure 7-8 and table 7-26 also clearly show that the machine-drilled holes lasted longer than the hand-drilled holes. All the machine-drilled holes used a pilot hole, which showed an average of 0.8 gouges per hole in machine drilling compared to an overall average of 1.5 gouges per hole in hand drilling, as shown in tables 7-1 and 7-2. This hole-quality difference likely accounts for the difference in fatigue lives. Table 7-27 shows that crack initiation accounted for about 84% of the life of the machine-drilled holes, while it accounted for only 62% of the life of hand-drilled holes. Cycles from initiation to failure, however, show no real difference between hand-drilled and machine-drilled holes, as shown in table 7-28. The fact that crack initiation was the difference between the fatigue lives of the two drilling methods supports the hypothesis that hole quality is the major factor in fatigue life of as-drilled holes.

Table 7-26. Drilling Method vs N_f (17.5 ksi)

```
Factor             Mean     StDev  ----+---------+---------+---------+--
Hand Drilled     100795      8445   (---------*---------)
Machine Drilled  283135    163791                 (-------*-------)
                                   ----+---------+---------+---------+--
p-value = 0.061                        0    150000    300000    450000
```

Table 7-27. Drilling Method vs N_i/N_f (17.5 ksi)

```
Factor             Mean     StDev  -------+---------+---------+---------
Hand Drilled    0.62345   0.03444   (-------*-------)
Machine Drilled 0.83858   0.06214                        (----*----)
                                   -------+---------+---------+---------
p-value = 0.004                          0.60      0.72      0.84
```

Table 7-28. Drilling Method vs N_f-N_i (17.5 ksi)

```
Factor             Mean     StDev  --+---------+---------+---------+----
Hand Drilled      35677      1017   (--------------*---------------)
Machine Drilled   44751     24372            (--------*--------)
                                   --+---------+---------+---------+----
p-value = 0.635                      0     25000     50000     75000
```

7.3.3 Testing at 25 ksi.

Fatigue testing at 25 ksi was conducted primarily for correlation with FASTRAN predictions. The test was composed of two each of polished TL and LT specimens and one as-drilled specimen (due to operator error). As expected, all specimens failed at similar numbers of cycles, ranging from about 45,000 to 60,000. The results corresponded well with the model predictions. The high-stress level yielded the material at the notch root and resulted in rapid failure. This level of stress eliminated any residual-stress or material effects.

7.3.4 Overload and Underload Tests.

The underloaded and overloaded specimens were tested at 21 ksi. Figure 7-10 shows a comparison of the fatigue lives of the various hole types at 21 ksi. The average life of the polished baseline specimens is represented by the solid line, and the average lives of the other specimen types are represented by the corresponding dashed lines. The polished, as-drilled, and underload specimens failed within fairly tight scatter bands, while the overload tests showed a surprising amount of scatter. The underload test resulted in about a 40% decrease in fatigue life, while the overload test resulted in fatigue lives about a factor of 18 longer, which were both greater than the FASTRAN respective predictions of 23% and a factor of 10.

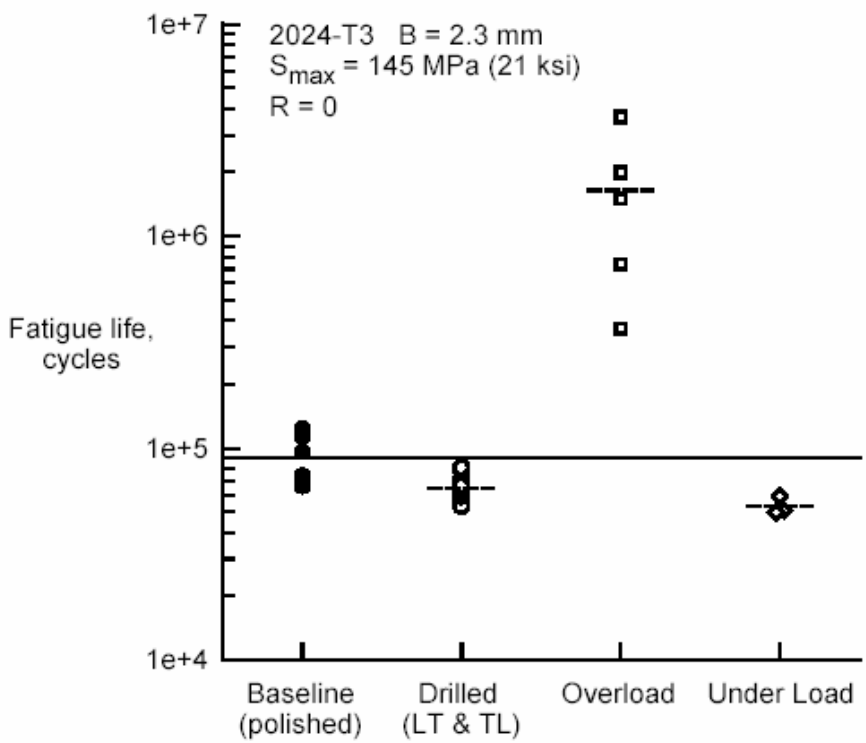


Figure 7-10. Fatigue Lives at 21 ksi

7.3.5 Fatigue Crack Surface Microscopy.

No correlation could be found between the crack initiation site and the type of specimen. Of the 20 specimens inspected, 14 (70%) had center cracks, which suggests that cracks are not as likely to initiate at the corners. In addition, none of the 20 specimens showed evidence of cracks initiating at the burrs.

SEM inspection of the initiation crack replicates corresponded fairly well with the optical microscopy estimates. The optical results gave an average approximate crack size at the edge of the hole of about 4 microns. The SEM measurements show a crack size of about 10 microns, as shown in figure 7-11.

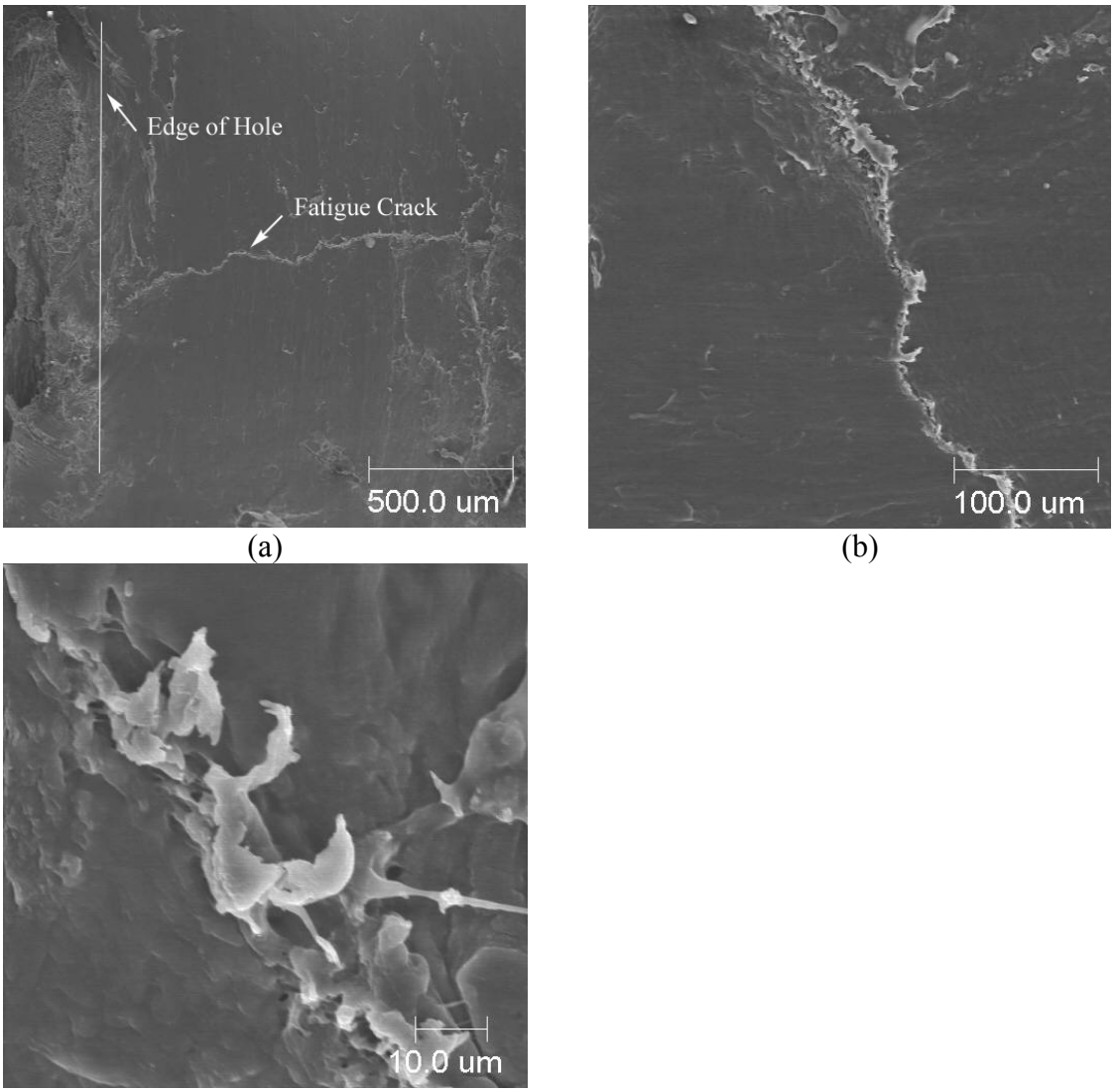


Figure 7-11. The SEM Micrograph of Crack Replicate at (a) 40-Times (b) 200-Times and (c) 1000-Times Magnification

In summary, the fatigue tests suggested that dull bits do induce residual compressive hoop stresses, resulting in longer lives, but machining marks create stress intensities that reduce the fatigue life much more than the extension caused by residual stresses. Machining effects, however, appear to balance out, so that there is not a large difference in the fatigue lives due to the different factors. This means that, although production conditions detract from the performance of aircraft fastener holes, there is no production condition that is extremely detrimental.

8. CONCLUSIONS.

This study investigated several production fastener hole drilling factors and their effects on hole quality, residual stress, and fatigue life. These tests were conducted with production-quality hand and machine drills and drill bits on 11- by 2- by 0.09-inch specimens of 2024-T3 aluminum. And these were compared with similar laboratory-quality specimens that were chemically polished to remove machining marks and residual stresses.

Hole quality was quantified in four categories: surface roughness, conicality, the number of gouge marks, and the angle of the gouge marks. The tests found that the use of a predrilled half-diameter hole, or pilot hole, most affected overall hole quality, and that hole quality was improved by its use. Other factors that affected hole quality were the length of the bit, the sharpness of the bit, the feed rate, and the experience of the operator.

X-ray diffraction was used in an attempt to measure residual stresses directly and nondestructively. A number of tests were conducted, and it was found that the best method was to concentrate the beam across the width of the hole bore while minimizing the height of the beam, and to use $\frac{2\theta}{\Omega}$ scans with Ψ psi tilts. Unfortunately, the tests gave inconsistent results due to a number of factors. One major factor was the curved geometry of the hole, which caused the beam to be incident upon the surface at continuously changing angles. Another factor was that the drilling process produced a rough surface. Both of these factors can alter the beam, giving misleading results. Another factor was that the aluminum had been rolled, creating texture, which can also give poor results. The overall effect led to such inconsistency that no meaningful comparison could be made between specimens.

Fatigue tests showed that the production-quality holes failed faster than the laboratory-quality holes. It was concluded that machining marks caused crack initiation sites, accounting for this difference. Among the as-drilled holes, those drilled with the old, dull bit lasted longer in fatigue compared to those drilled with new, sharp bits. This is especially revealing in the set of machine-drilled holes, which were all drilled with a pilot hole, because this produced the best quality in the hole-quality tests. In these machine-drilled holes, the only difference was that some of the holes were drilled with the old bit and some with the new bit, which showed no discernable difference in hole quality. Those drilled with the old bit lasted longer in fatigue, suggesting that the old bit induced more beneficial hoop stresses. However, hole quality remained a more significant factor in fatigue life than residual stress.

9. RECOMMENDATIONS.

Often in seeking answers, one finishes with more questions than when they started. This project was no different, and many questions arose that were either out of the scope of the research or required additional resources that could not be justified. Recommendations for future work fall into two categories: additional testing and better models.

9.1 ADDITIONAL TESTING.

One goal of this research was to improve manufacturing procedures. The drilling of the fastener holes is only one part of the whole process of joining aircraft parts, and other areas of the procedure should be examined. In particular, the next step of riveting should be investigated. Riveting is a highly dynamic procedure that consists of inserting or driving the rivet into the hole and plastically deforming the rivet by hammering. The rivet is obviously deformed, but the fastener hole may also be deformed axially, radially, or randomly. These deformations may pinch the collar of the hole or induce compressive residual hoop stresses, benefiting the fatigue life, they may form cracks or additional crack initiation sites, or result in fretting fatigue during cycling. All these factors, and more, may either wipe out, negate, or intensify the drilling effects, and the fatigue performance of riveted fastener holes should be investigated. Many studies have already been conducted on the riveting process, but again, they often are sterilized by laboratory procedures, eliminating many manufacturing effects that may prove critical. In response to this need, specimens have been prepared in the same manner as the fatigue tests, and an MS20470D6 rivet was installed at the Delta repair hanger. These specimens will be tested as part of another study at 17.5 ksi.

The AGARD R-732 study suggested that holes polished for 1 minute lasted much longer than predicted because the machining marks had been eliminated or greatly diminished while the residual stresses remained. Additional fatigue testing of specimens drilled under the same conditions as those in the fatigue tests, but polished for 1 minute, may provide better evidence of the effect of the residual stresses, apart from the effects of hole quality. This would allow for a more rigorous comparison to the polished holes on the basis of residual-stress effects alone, providing a reasonable estimate of the magnitude of the stress.

Residual-stress formation and hole quality may be material-dependent. Since the industry now commonly uses the 7050 series aluminums, identical hole-quality and fatigue tests with this material would be advisable.

9.2 MECHANICAL MODELING.

Residual-stress analysis was complicated in this study by the hole-quality effects. If an initial flaw size could be assumed, the fatigue life could then be used to estimate the magnitude of the residual stress. Due to the different shapes of the gouge marks, it would be difficult to estimate such a flaw size. What is needed is a model relating stress intensity to the gouge mark geometry. This model would need to take into account the size of the gouge, the angle of incidence of the gouge to the bore, and the shape of the gouge.

The cause of the gouging is still a mystery. The independence of the gouge angle to the feed rate of the bit eliminates the most obvious guesses. The straying of the operator's hand and the deflection of the tip of the bit seems to explain the angle of the gouges, but cannot explain the regularity of angle. Explaining the formation of the gouges would help determine how to eliminate the gouges, thus extending fatigue life.

9.3 IMPROVED BURR FORMATION MODEL.

Existing models of the formation of the burr only take into account localized bending of excess material at the exit face of the hole. The presence of burrs on the entry face and the geometry of the bulge burrs are evidence that axial-plastic deformation contributes to the formation of the burr, and material from deeper inside the bore of the hole may make up the burr. An improved burr formation model is needed to more accurately represent the condition of the hole after drilling, and especially the residual stresses induced by the drilling process.

9.4 FASTENER HOLE PRODUCTION.

Production of fastener holes can be improved to increase the fatigue life of aircraft structural joints and to improve the quality of the holes. The use of pilot holes as standard practice would be the most beneficial practice. This requires more production time, however, and a serious analysis of the cost benefit should be performed before making such a change.

Individual drill bits should be used as long as practical in production, since they offer improved fatigue life without a significant reduction in hole quality. This practice would not greatly increase drilling time, but could partially be offset by the reduced frequency of changing bits, as well as the purchase of fewer bits.

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APPENDIX A—EXPERIMENTAL TEST DATA

Table A-1. Hole-Quality Test Matrix

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure	Bit Speed
Experienced	No	Long	New	High	Stopped
Experienced	No	Long	New	Low	Full
Experienced	No	Long	New	High	Stopped
Experienced	No	Long	New	High	Stopped
Experienced	No	Long	New	Low	Full
Experienced	No	Long	New	Low	Full
Experienced	No	Long	Old	Low	Stopped
Experienced	No	Long	Old	Low	Stopped
Experienced	No	Long	Old	High	Full
Experienced	No	Long	Old	Low	Stopped
Experienced	No	Long	Old	High	Full
Experienced	No	Long	Old	High	Full
Experienced	No	Short	New	Low	Stopped
Experienced	No	Short	New	Low	Stopped
Experienced	No	Short	New	High	Full
Experienced	No	Short	New	High	Full
Experienced	No	Short	New	High	Full
Experienced	No	Short	New	Low	Stopped
Experienced	No	Short	Old	Low	Full
Experienced	No	Short	Old	High	Stopped
Experienced	No	Short	Old	Low	Full
Experienced	No	Short	Old	High	Stopped
Experienced	No	Short	Old	High	Stopped
Experienced	No	Short	Old	Low	Full
Experienced	Yes	Long	New	High	Full
Experienced	Yes	Long	New	High	Full
Experienced	Yes	Long	New	Low	Stopped
Experienced	Yes	Long	New	Low	Stopped
Experienced	Yes	Long	New	High	Full
Experienced	Yes	Long	New	Low	Stopped
Experienced	Yes	Long	Old	High	Stopped
Experienced	Yes	Long	Old	Low	Full
Experienced	Yes	Long	Old	Low	Full
Experienced	Yes	Long	Old	Low	Full
Experienced	Yes	Long	Old	High	Stopped
Experienced	Yes	Long	Old	High	Stopped
Experienced	Yes	Short	New	High	Stopped

Table A-1. Hole-Quality Test Matrix (Continued)

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure	Bit Speed
Experienced	Yes	Short	New	High	Stopped
Experienced	Yes	Short	New	Low	Full
Experienced	Yes	Short	New	Low	Full
Experienced	Yes	Short	New	Low	Full
Experienced	Yes	Short	New	High	Stopped
Experienced	Yes	Short	Old	Low	Stopped
Experienced	Yes	Short	Old	High	Full
Experienced	Yes	Short	Old	High	Full
Experienced	Yes	Short	Old	Low	Stopped
Experienced	Yes	Short	Old	High	Full
Experienced	Yes	Short	Old	Low	Stopped
Novice	No	Long	New	High	Stopped
Novice	No	Long	New	Low	Full
Novice	No	Long	New	High	Stopped
Novice	No	Long	New	High	Stopped
Novice	No	Long	New	Low	Full
Novice	No	Long	New	Low	Full
Novice	No	Long	Old	Low	Stopped
Novice	No	Long	Old	Low	Stopped
Novice	No	Long	Old	High	Full
Novice	No	Long	Old	Low	Stopped
Novice	No	Long	Old	High	Full
Novice	No	Long	Old	High	Full
Novice	No	Short	New	Low	Stopped
Novice	No	Short	New	Low	Stopped
Novice	No	Short	New	High	Full
Novice	No	Short	New	High	Full
Novice	No	Short	New	High	Full
Novice	No	Short	New	Low	Stopped
Novice	No	Short	Old	Low	Full
Novice	No	Short	Old	High	Stopped
Novice	No	Short	Old	Low	Full
Novice	No	Short	Old	High	Stopped
Novice	No	Short	Old	High	Stopped
Novice	No	Short	Old	Low	Full
Novice	Yes	Long	New	High	Full
Novice	Yes	Long	New	High	Full
Novice	Yes	Long	New	Low	Stopped
Novice	Yes	Long	New	Low	Stopped

Table A-1. Hole-Quality Test Matrix (Continued)

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure	Bit Speed
Novice	Yes	Long	New	High	Full
Novice	Yes	Long	New	Low	Stopped
Novice	Yes	Long	Old	High	Stopped
Novice	Yes	Long	Old	Low	Full
Novice	Yes	Long	Old	Low	Full
Novice	Yes	Long	Old	Low	Full
Novice	Yes	Long	Old	High	Stopped
Novice	Yes	Long	Old	High	Stopped
Novice	Yes	Short	New	High	Stopped
Novice	Yes	Short	New	High	Stopped
Novice	Yes	Short	New	Low	Full
Novice	Yes	Short	New	Low	Full
Novice	Yes	Short	New	Low	Full
Novice	Yes	Short	New	High	Stopped
Novice	Yes	Short	Old	Low	Stopped
Novice	Yes	Short	Old	High	Full
Novice	Yes	Short	Old	High	Full
Novice	Yes	Short	Old	Low	Stopped
Novice	Yes	Short	Old	High	Full
Novice	Yes	Short	Old	Low	Stopped

Table A-2. Complete Hole-Quality Data

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure or Feed Rate	Bit Speed	Hole	Specimen	Gouge Angle	Gouge Number	Roughness	Solid Angle	Curling Burr	Triangular Burr	Bulge Burr
Machine	No	Short	Old	Low	Full	01-1	A89N8-10	12.3	1	1.065	3.6	0	2	0
Machine	No	Short	Old	Low	Full	02-1	A89N8-10	0.0	0	1.041	1.7	0	2	0
Machine	No	Short	Old	Low	Full	03-1	A89N8-10	0.0	0	1.044	1.1	1	1	0
Machine	Yes	Short	Old	High	Full	04-1	A89N8-10	6.1	1	1.054	0.2	1	1	0
Machine	Yes	Short	Old	High	Full	05-1	A89N8-10	9.9	1	1.096	0.2	2	0	0
Machine	Yes	Short	Old	High	Full	06-1	A89N8-10	0.0	0	1.064	1.5	2	0	0
Machine	No	Long	Old	High	Full	07-1	A89N8-10	2.3	2	1.069	2.7	0	1	1
Machine	No	Long	Old	High	Full	08-1	A89N8-10	2.3	4	1.112	5.4	1	1	0
Machine	No	Long	Old	High	Full	09-1	A89N8-10	10.4	3	1.147	4.3	0	2	0
Machine	Yes	Long	Old	Low	Full	10-1	A89N8-10	0.0	0	1.125	1.3	1	1	0
Machine	Yes	Long	Old	Low	Full	11-1	A89N8-10	0.6	4	1.067	1.2	1	1	0
Machine	Yes	Long	Old	Low	Full	12-1	A89N8-10	0.0	0	1.089	0.6	2	0	0
Machine	No	Short	New	High	Full	13-1	A89N8-10	0.0	0	1.070	3.2	1	1	0
Machine	No	Short	New	High	Full	14-1	A89N8-10	3.9	5	1.053	1.6	0	1	1
Machine	No	Short	New	High	Full	15-1	A89N8-10	0.5	4	1.046	0.8	0	2	0
Machine	Yes	Short	New	Low	Full	16-1	A89N8-10	0.0	0	1.074	0.3	0	2	0
Machine	Yes	Short	New	Low	Full	17-1	A89N8-10	0.0	0	1.066	2.0	1	1	0
Machine	Yes	Short	New	Low	Full	18-1	A89N8-10	0.0	0	1.056	1.3	2	0	0
Machine	No	Long	New	Low	Full	19-1	A89N8-10	16.8	2	1.063	9.6	1	1	0
Machine	Yes	Long	New	High	Full	19-3	A89N8-10	9.2	2	1.082	-0.4	1	1	0
Machine	No	Long	New	Low	Full	20-1	A89N8-10	14.8	1	1.079	4.6	1	0	0
Machine	Yes	Long	New	High	Full	20-3	A89N8-10	12.1	1	1.074	0.1	2	0	0
Machine	No	Long	New	Low	Full	21-1	A89N8-10	9.1	1	1.094	8.5	1	1	0
Machine	Yes	Long	New	High	Full	21-3	A89N8-10	0.0	0	1.067	0.1	2	0	0
Experienced	No	Long	New	High	Stopped	01-1	A90N8-12	0.0	0	1.085	6.4	0	0	1

Table A-2. Complete Hole-Quality Data (Continued)

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure or Feed Rate	Bit Speed	Hole	Specimen	Gouge Angle	Gouge Number	Roughness	Solid Angle	Curling Burr	Triangular Burr	Bulge Burr
Experienced	No	Long	New	Low	Full	01-2	A90N8-12	10.8	3	1.061	7.3	0	0	2
Experienced	No	Long	New	Low	Full	02-2	A90N8-12	5.0	2	0.046	9.7	0	0	2
Experienced	No	Long	New	Low	Full	02-3	A90N8-12	6.1	2	1.089	5.5	0	2	0
Experienced	No	Long	New	High	Stopped	05-1	A90N8-12	0.0	0	1.084	9.3	2	0	0
Experienced	No	Long	New	High	Stopped	05-2	A90N8-12	2.2	1			0	1	0
Experienced	No	Short	New	Low	Stopped	05-3	A90N8-12	9.2	1	1.088	14.0	0	1	0
Experienced	No	Short	New	Low	Stopped	06-1	A90N8-12	0.6	1	1.146	11.8	0	0	1
Experienced	No	Short	New	High	Full	06-2	A90N8-12	0.0	0	1.090	12.8	0	0	1
Experienced	No	Short	New	High	Full	06-3	A90N8-12	14.8	2	1.056	5.1	0	1	0
Experienced	No	Short	New	High	Full	07-1	A90N8-12	24.1	1	1.106	6.6	0	0	0
Experienced	No	Short	New	Low	Stopped	07-2	A90N8-12	4.9	3	1.127	7.1	0	0	0
Experienced	No	Short	Old	Low	Full	08-1	A90N8-12	9.0	2	1.095	18.1	0	0	0
Experienced	No	Short	Old	High	Stopped	08-2	A90N8-12	13	3	1.109	6.0	0	0	0
Experienced	No	Short	Old	Low	Full	08-3	A90N8-12	2.2	1	1.122	6.3	0	2	0
Experienced	No	Short	Old	High	Stopped	09-1	A90N8-12	6.9	1	1.059	5.6	0	1	1
Experienced	No	Short	Old	High	Stopped	09-2	A90N8-12	3.4	2	1.058	2.8	0	0	2
Experienced	No	Short	Old	Low	Full	09-3	A90N8-12	3.8	3	1.151	8.4	1	1	0
Experienced	No	Long	Old	Low	Stopped	10-1	A90N8-12	4.5	3	1.082	6.1	0	2	0
Experienced	No	Long	Old	Low	Stopped	10-2	A90N8-12	5.3	3	1.152	9.3	0	0	1
Experienced	No	Long	Old	High	Full	10-3	A90N8-12	2.3	3	1.079	3.7	0	2	0
Experienced	No	Long	Old	Low	Stopped	11-1	A90N8-12	3.8	2	1.071	5.5	0	2	0
Experienced	No	Long	Old	High	Full	11-2	A90N8-12	7.0	3	1.097	7.9	0	2	0
Experienced	No	Long	Old	High	Full	11-3	A90N8-12	0.9	1	1.074	5.9	0	2	0
Experienced	Yes	Long	New	High	Full	01-1	A90N8-3	0.0	0	1.054	1.7	0	0	2

Table A-2. Complete Hole-Quality Data (Continued)

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure or Feed Rate	Bit Speed	Hole	Specimen	Gouge Angle	Gouge Number	Roughness	Solid Angle	Curling Burr	Triangular Burr	Bulge Burr
Experienced	Yes	Long	New	High	Full	01-2	A90N8-3	1.5	2	1.046	3.9	0	1	1
Experienced	Yes	Long	New	Low	Stopped	01-3	A90N8-3	0.5	1	1.063	3.1	0	2	0
Experienced	Yes	Long	New	Low	Stopped	02-1	A90N8-3	4.4	2	1.042	0.3	0	1	1
Experienced	Yes	Long	New	High	Full	02-2	A90N8-3	1.8	1	1.028	5.2	0	0	1
Experienced	Yes	Long	New	Low	Stopped	02-3	A90N8-3	2.0	1	1.038	2.1	0	2	0
Experienced	Yes	Long	Old	High	Stopped	03-1	A90N8-3	1.7	5	1.064	4.1	0	0	1
Experienced	Yes	Long	Old	Low	Full	03-2	A90N8-3	2.3	2	1.075	5.7	0	0	0
Experienced	Yes	Long	Old	Low	Full	03-3	A90N8-3	4.9	1	1.047	7.5	0	0	1
Experienced	Yes	Long	Old	Low	Full	04-1	A90N8-3	4.8	2	1.038	6.8	0	0	0
Experienced	Yes	Long	Old	High	Stopped	04-2	A90N8-3	4.2	2	1.051	12.4	0	1	0
Experienced	Yes	Long	Old	High	Stopped	04-3	A90N8-3	4.0	1	1.047	6.9	0	0	2
Experienced	Yes	Short	New	High	Stopped	05-1	A90N8-3	0.0	0	1.041	2.4	0	0	2
Experienced	Yes	Short	New	High	Stopped	05-2	A90N8-3	7.0	1	1.037	3.4	0	0	2
Experienced	Yes	Short	New	Low	Full	05-3	A90N8-3	0.1	1	1.058	3.5	0	0	1
Experienced	Yes	Short	New	Low	Full	06-1	A90N8-3	1.4	1	1.029	3.7	0	0	2
Experienced	Yes	Short	New	Low	Full	06-2	A90N8-3	4.5	3	1.023	2.2	0	0	0
Experienced	Yes	Short	New	High	Stopped	06-3	A90N8-3	0.4	1	1.052	1.3	0	0	2
Experienced	Yes	Short	Old	Low	Stopped	07-1	A90N8-3	0.8	1	1.080	7.1	0	0	0
Experienced	Yes	Short	Old	High	Full	07-2	A90N8-3	2.8	4	1.046	6.1	0	0	0
Experienced	Yes	Short	Old	High	Full	08-2	A90N8-3	0.8	7	1.051	0.6	0	0	2
Experienced	Yes	Short	Old	Low	Stopped	08-3	A90N8-3	5.0	3	1.059	6.7	0	1	1
Experienced	Yes	Short	Old	High	Full	09-1	A90N8-3	5.2	1	1.050	8.1	0	0	2
Experienced	Yes	Short	Old	Low	Stopped	09-2	A90N8-3	4.7	3	1.047	6.8	0	0	2
Novice	Yes	Long	New	High	Full	01-1	A94N8-9	1.5	3	1.058	3.9	0	0	2

Table A-2. Complete Hole-Quality Data (Continued)

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure or Feed Rate	Bit Speed	Hole	Specimen	Gouge Angle	Gouge Number	Roughness	Solid Angle	Curling Burr	Triangular Burr	Bulge Burr
Novice	Yes	Long	New	High	Full	01-2	A94N8-9	0.0	2	1.057	3.9	0	0	1
Novice	Yes	Long	New	Low	Stopped	01-3	A94N8-9	0.3	1	1.081	5.5	0	0	2
Novice	Yes	Long	New	Low	Stopped	02-1	A94N8-9	0.9	2	1.077	4.2	0	0	0
Novice	Yes	Long	New	High	Full	02-2	A94N8-9	0.0	0	1.004	4.2	0	0	0
Novice	Yes	Long	New	Low	Stopped	02-3	A94N8-9	3.5	1	1.087	5.5	0	1	1
Novice	Yes	Long	Old	High	Stopped	03-1	A94N8-9	0.0	0	1.090	7.4	0	0	2
Novice	Yes	Long	Old	Low	Full	03-2	A94N8-9	0.3	2	1.098	7.1	0	1	0
Novice	Yes	Long	Old	Low	Full	03-3	A94N8-9	2.5	1	1.113	2.7	0	0	1
Novice	Yes	Long	Old	Low	Full	04-1	A94N8-9	1.5	1	1.056	5.1	0	0	0
Novice	Yes	Long	Old	High	Stopped	04-2	A94N8-9	0.6	1	1.093	12	0	0	0
Novice	Yes	Long	Old	High	Stopped	04-3	A94N8-9	1.7	1	1.050	1.5	0	0	2
Novice	Yes	Short	New	High	Stopped	05-1	A94N8-9	0.0	0	1.042	6.2	0	0	0
Novice	Yes	Short	New	High	Stopped	05-2	A94N8-9	1.2	4	-0.013	3.4	0	0	0
Novice	Yes	Short	New	Low	Full	05-3	A94N8-9	2.9	3	1.074	5.2	0	0	0
Novice	Yes	Short	New	Low	Full	06-1	A94N8-9	0.0	0	1.051	3.2	0	0	0
Novice	Yes	Short	New	Low	Full	06-2	A94N8-9	0.0	0	1.046	2.5	0	0	0
Novice	Yes	Short	New	High	Stopped	06-3	A94N8-9	0.2	3	1.041	2.2	0	0	0
Novice	Yes	Short	Old	Low	Stopped	07-1	A94N8-9	2.9	1	1.059	4.6	0	0	0
Novice	Yes	Short	Old	High	Full	07-2	A94N8-9	2.7	2	1.094	8.7	0	0	0
Novice	Yes	Short	Old	High	Full	07-3	A94N8-9	0.0	0	1.060	2.1	0	0	2
Novice	Yes	Short	Old	Low	Stopped	08-1	A94N8-9	0.6	2	1.056	5.4	0	0	0
Novice	Yes	Short	Old	High	Full	08-2	A94N8-9	0.4	2	1.028	2.3	0	0	0
Novice	Yes	Short	Old	Low	Stopped	08-3	A94N8-9	0.2	2	1.093	8.0	0	0	0
Novice	No	Long	New	High	Stopped	01-1	A96N8-11	0.0	0	1.206	0.4	0	0	0

Table A-2. Complete Hole-Quality Data (Continued)

Operator	Pilot Hole	Bit Length	Bit Condition	Pressure or Feed Rate	Bit Speed	Hole	Specimen	Gouge Angle	Gouge Number	Roughness	Solid Angle	Curling Burr	Triangular Burr	Bulge Burr
Novice	No	Long	New	Low	Full	01-2	A96N8-11	0.0	0	1.072	5.2	1	0	0
Novice	No	Long	New	High	Stopped	01-3	A96N8-11	3.2	1	1.079	2.6	0	2	0
Novice	No	Long	New	High	Stopped	02-1	A96N8-11	3.8	2	1.052	5.7	0	1	1
Novice	No	Long	New	Low	Full	02-2	A96N8-11	12.0	1	1.051	6.4	0	0	1
Novice	No	Long	New	Low	Full	02-3	A96N8-11	12.5	1	1.056	7.4	0	2	0
Novice	No	Long	Old	Low	Stopped	03-1	A96N8-11	5.4	1	1.061	7.9	0	2	0
Novice	No	Long	Old	Low	Stopped	03-2	A96N8-11	15.4	1	1.033	0.8	1	0	0
Novice	No	Long	Old	High	Full	03-3	A96N8-11	0.0	0	1.042	2.2	0	1	0
Novice	No	Long	Old	Low	Stopped	04-1	A96N8-11	14	1	1.106	8.5	0	2	0
Novice	No	Long	Old	High	Full	04-2	A96N8-11	16.1	1	1.072	0.0	0	0	0
Novice	No	Long	Old	High	Full	04-3	A96N8-11	0.0	0	1.056	4.2	0	1	1
Novice	No	Short	New	Low	Stopped	05-1	A96N8-11	16.2	1	1.097	10.8	0	0	1
Novice	No	Short	New	Low	Stopped	05-2	A96N8-11	2.1	2	1.092	10.4	0	1	0
Novice	No	Short	New	High	Full	05-3	A96N8-11	0.9	1	1.051	5.4	0	2	0
Novice	No	Short	New	High	Full	06-1	A96N8-11	1.3	1	1.117	13.9	0	0	1
Novice	No	Short	New	High	Full	06-3	A96N8-11	0.0	0	1.095	14.6	0	2	0
Novice	No	Short	New	Low	Stopped	07-1	A96N8-11	2.1	2	1.082	9.0	1	1	0
Novice	No	Short	Old	Low	Full	08-1	A96N8-11	0.9	1	1.048	6.6	0	2	0
Novice	No	Short	Old	Low	Full	08-2	A96N8-11	0.0	0	1.120	26.3	0	2	0
Novice	No	Short	Old	High	Stopped	08-3	A96N8-11	3.9	1	1.128	13.7	0	1	1
Novice	No	Short	Old	High	Stopped	09-1	A96N8-11	0.0	0	1.046	10.4	0	2	0
Novice	No	Short	Old	High	Stopped	09-2	A96N8-11	0.0	0					
Novice	No	Short	Old	Low	Full	09-3	A96N8-11	0.0	0	1.119	5.2	0	1	0

Table A-3. Complete Fatigue Test Data

Specimen	Type	Test	Load (ksi)	Ni_1	Ni_2	Nf	Crack Site	Comments
A89N8-14	HD	Old, No PH	21	48400	55400	64856	Center	
A89N8-3	HD	Old, PH	21	48200	50900	59420	Corner	
A89N8-9	HD	New, No PH	21	36400	46200	57692	Corner	
A90N8-10	HD	New, PH	21	45600	55700	68953	Center	
A90N8-15	HD	New, No PH	21			67622		
A91N8-12	HD	New, PH	17.5			111309		
A91N8-14	HD	New, PH	21	50300	51900	64183	Center	
A91N8-3	HD	New, PH	21			71148		
A91N8-8	HD	Old, No PH	21	57800	63400	63400		
A93N8-10	HD	Old, No PH	21			62340		
A93N8-15	HD	Old, PH	25	31000	46000	49078	Center	
A93N8-3	HD	Old, PH	21	66400	69000	78957	Corner	
A93N8-4	HD	New, No PH	21			56163		
A93N8-8	HD	Old, No PH	17.5	54400		90796	Center	
A94N8-12	HD	New, PH	21	31800	40900	53209	Corner	
A94N8-14	HD	New, PH	21	30600	57400	65254	Center	
A94N8-6	HD	Old, PH	21	64200		80885	Center	
A95N8-14	HD	Old, PH	17.5	64300		99258		
A95N8-2	HD	New, No PH	21	30200	47000	60884	Center	
A95N8-3	HD	Old, No PH	21			62523		
A95N8-7	HD	New, No PH	17.5			101817		
A96N8-10	HD	Old, No PH	21	38800	49700	59208	Center	
A96N8-3	HD	New, No PH	21	46500	55600	62373	Corner	
A96N8-6	HD	Old, PH	21	51400	58200	66119	Center	
A92N8-1	LT	Baseline	21			96064		
A92N8-10	LT	Baseline	21	56400	63400	73777		
A92N8-11	LT	Underload	21			50969		
A92N8-12	LT	Baseline	25			51888		
A92N8-13	LT	Overload	21			1997564		
A92N8-15	LT	Overload	21			737452	Center	
A92N8-2	LT	Underload	21			52016		
A92N8-4	LT	Baseline	21	61900				Overloaded
A92N8-5	LT	Baseline	21	108500		129768		
A92N8-6	LT	Baseline	17.5			4942664		Runout
A92N8-7	LT	Baseline	25	16800	18800	62269	Center	
A92N8-8	LT	Baseline	17.5			380187		Crack on one side ONLY
A92N8-9	LT	Baseline	21	20100	51400	66144	Corner	
A90N8-14	MD	Old, PH	17.5	211100	280200	288603		

Table A-3. Complete Fatigue Test Data (Continued)

Specimen	Type	Test	Load (ksi)	Ni_1	Ni_2	Nf	Crack Site	Comments
A91N8-2	MD	Old, PH	17.5	532800	596100	600672		
A91N8-6	MD	New, PH	17.5	208900	247200	251573		
A93N8-7	MD	Old, PH	17.5	195100	222100	237331		
A96N8-5	MD	New, PH	17.5	134200	139700	157655		
A97N8-3	MD	New, PH	17.5	148200	149700	162974		Initiation suspect due to low battery
A34N7-12-TL	TL	Overload	21			1500732		
A34N7-13-TL	TL	Overload	21					Failed at grips
A34N7-15-TL	TL	Baseline	21			123463		
A34N7-2-TL	TL	Baseline	25	16100	40400	43809	Center	
A34N7-4-TL	TL	Underload	21			58888		
A34N7-5-TL	TL	Overload	21			366014		
A34N7-6-TL	TL	Baseline	21			113694		
A34N7-8-TL	TL	Baseline	25			62231		
A34N7-9-TL	TL	Baseline	21	44600		67844	Center	
A97N8-11-TL	TL	Overload	21			3655454		Runout
A97N8-14-TL	TL	Overload	21					Bent
A97N8-5-TL	TL	Baseline	17.5			3027062		Runout
A97N8-6-TL	TL	Underload	21			49612		
A97N8-7-TL	TL	Baseline	17.5			3005205		Runout

APPENDIX B—MINITAB STATISTICAL OUTPUT

Hand-Drilled Hole Quality

```
One-way ANOVA: Roughness versus Operator

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Operator    1    0.0001    0.0001     0.00    0.955
Error      92    2.2824    0.0248
Total      93    2.2825
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
A          47    1.0487    0.1528  (---------------*--------------)
B          47    1.0506    0.1621   (--------------*--------------)
                                   ------+---------+---------+---------+
Pooled StDev =   0.1575                1.020     1.050     1.080     1.110
```

```
One-way ANOVA: Roughness versus Pilot Hole

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Pilot Ho    1    0.0225    0.0225     0.92    0.341
Error      92    2.2600    0.0246
Total      93    2.2825
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --------+---------+---------+--------
No Pilot   46    1.0654    0.1575          (------------*-------------)
Pilot Ho   48    1.0345    0.1560   (------------*-----------)
                                   --------+---------+---------+--------
Pooled StDev =   0.1567                  1.015     1.050     1.085
```

```
One-way ANOVA: Roughness versus Bit Length

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Bit Leng    1    0.0002    0.0002     0.01    0.926
Error      92    2.2823    0.0248
Total      93    2.2825
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Long       47    1.0481    0.1528  (--------------*---------------)
Short      47    1.0512    0.1621   (--------------*---------------)
                                   ------+---------+---------+---------+
Pooled StDev =   0.1575                1.020     1.050     1.080     1.110
```

```
One-way ANOVA: Roughness versus Bit Condition

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Bit Cond    1    0.0603    0.0603     2.50    0.117
Error      92    2.2222    0.0242
Total      93    2.2825
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
New        47    1.0243    0.2176   (----------*----------)
Old        47    1.0750    0.0307               (-----------*----------)
                                   ------+---------+---------+---------+
Pooled StDev =   0.1554                1.000     1.040     1.080     1.120


One-way ANOVA: Roughness versus Pressure

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Pressure    1    0.0032    0.0032     0.13    0.720
Error      92    2.2793    0.0248
Total      93    2.2825
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --------+---------+---------+--------
High       46    1.0437    0.1627   (--------------*--------------)
Low        48    1.0554    0.1522       (--------------*--------------)
                                   --------+---------+---------+--------
Pooled StDev =   0.1574                  1.020     1.050     1.080


One-way ANOVA: Roughness versus Bit Speed

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Bit Spee    1    0.0008    0.0008     0.03    0.860
Error      92    2.2817    0.0248
Total      93    2.2825
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
Full       48    1.0468    0.1506   (--------------*--------------)
Stopped    46    1.0526    0.1643    (---------------*--------------)
                                   -------+---------+---------+---------
Pooled StDev =   0.1575                 1.020     1.050     1.080


One-way ANOVA: Conicality versus Operator

Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Operator    1       0.0       0.0     0.00    0.968
Error      92    1569.2      17.1
Total      93    1569.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
A          47     6.230     3.566   (----------------*----------------)
B          47     6.264     4.626   (----------------*----------------)
                                   ---------+---------+---------+-------
Pooled StDev =    4.130                   5.60      6.30      7.00
```

```
One-way ANOVA: Conicality versus Pilot Hole

Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Pilot Ho    1     217.3     217.3    14.79    0.000
Error      92    1352.0      14.7
Total      93    1569.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
No Pilot   46     7.800     4.768                      (------*------)
Pilot Ho   48     4.758     2.646  (-------*------)
                                   ------+---------+---------+---------+
Pooled StDev =    3.833                4.5       6.0       7.5       9.0


One-way ANOVA: Conicality versus Bit Length

Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Bit Leng    1      78.7      78.7     4.86    0.030
Error      92    1490.6      16.2
Total      93    1569.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Long       47     5.332     2.863   (--------*---------)
Short      47     7.162     4.920                 (---------*--------)
                                   ------+---------+---------+---------+
Pooled StDev =    4.025                4.8       6.0       7.2       8.4


One-way ANOVA: Conicality versus Bit Condition

Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Bit Cond    1      23.5      23.5     1.40    0.240
Error      92    1545.8      16.8
Total      93    1569.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
New        47     5.747     3.639   (----------*-----------)
Old        47     6.747     4.513            (----------*-----------)
                                   -----+---------+---------+---------+-
Pooled StDev =    4.099               5.0       6.0       7.0       8.0


One-way ANOVA: Conicality versus Pressure

Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Pressure    1      34.0      34.0     2.04    0.157
Error      92    1535.3      16.7
Total      93    1569.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
High       46     5.633     3.817  (-----------*-----------)
Low        48     6.835     4.326              (----------*-----------)
                                   ------+---------+---------+---------+
Pooled StDev =    4.085                5.0       6.0       7.0       8.0
```

One-way ANOVA: Conicality versus Bit Speed

```
Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Bit Spee    1       0.0       0.0     0.00    0.970
Error      92    1569.2      17.1
Total      93    1569.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
Full       48     6.263     4.601    (---------------*----------------)
Stopped    46     6.230     3.572   (----------------*----------------)
                                   ---------+---------+---------+-------
Pooled StDev =    4.130                   5.60      6.30      7.00
```

One-way ANOVA: Gouge Angle versus Operator

```
Analysis of Variance for Gouge An
Source     DF        SS        MS        F        P
Operator    1      50.2      50.2     2.38    0.127
Error      92    1944.3      21.1
Total      93    1994.5
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --------+---------+---------+--------
A          47     4.306     4.509              (----------*----------)
B          47     2.845     4.684   (----------*----------)
                                   --------+---------+---------+--------
Pooled StDev =    4.597                  2.4       3.6       4.8
```

One-way ANOVA: Gouge Angle versus Pilot Hole

```
Analysis of Variance for Gouge An
Source     DF        SS        MS        F        P
Pilot Ho    1     292.8     292.8    15.83    0.000
Error      92    1701.8      18.5
Total      93    1994.5
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
No Pilot   46     5.378     5.849                   (-----*-----)
Pilot Ho   48     1.848     1.857  (-----*-----)
                                   -------+---------+---------+---------
Pooled StDev =    4.301                 2.0       4.0       6.0
```

One-way ANOVA: Gouge Angle versus Bit Length

```
Analysis of Variance for Gouge An
Source     DF        SS        MS        F        P
Bit Leng    1       1.0       1.0     0.05    0.827
Error      92    1993.5      21.7
Total      93    1994.5
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
Long       47     3.681     4.303     (----------------*----------------)
Short      47     3.470     4.982   (---------------*----------------)
                                   ----+---------+---------+---------+--
Pooled StDev =    4.655               2.40      3.20      4.00      4.80
```

```
One-way ANOVA: Gouge Angle versus Bit Condition

Analysis of Variance for Gouge An
Source     DF        SS        MS        F        P
Bit Cond    1       0.8       0.8     0.04    0.848
Error      92    1993.7      21.7
Total      93    1994.5
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
New        47     3.483     5.196   (----------------*---------------)
Old        47     3.668     4.042     (----------------*----------------)
                                   ----+---------+---------+---------+--
Pooled StDev =    4.655              2.40      3.20      4.00      4.80


One-way ANOVA: Gouge Angle versus Pressure

Analysis of Variance for Gouge An
Source     DF        SS        MS        F        P
Pressure    1      27.0      27.0     1.26    0.264
Error      92    1967.6      21.4
Total      93    1994.5
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
High       46     3.028     4.953   (----------*-----------)
Low        48     4.100     4.286           (----------*----------)
                                   -------+---------+---------+---------
Pooled StDev =    4.625                 2.4       3.6       4.8


One-way ANOVA: Gouge Angle versus Bit Speed

Analysis of Variance for Gouge An
Source     DF        SS        MS        F        P
Bit Spee    1       0.0       0.0     0.00    0.999
Error      92    1994.5      21.7
Total      93    1994.5
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---+---------+---------+---------+---
Full       48     3.575     5.107   (----------------*---------------)
Stopped    46     3.576     4.134   (----------------*----------------)
                                   ---+---------+---------+---------+---
Pooled StDev =    4.656              2.40      3.20      4.00      4.80
One-way ANOVA: Gouge Number versus Operator

Analysis of Variance for Gouge Nu
Source     DF        SS        MS        F        P
Operator    1     13.79     13.79     9.78    0.002
Error      92    129.70      1.41
Total      93    143.49
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
A          47     1.872     1.361                     (--------*-------)
B          47     1.106     0.983  (--------*-------)
                                   -+---------+---------+---------+-----
Pooled StDev =    1.187            0.80      1.20      1.60      2.00
```

```
One-way ANOVA: Gouge Number versus Pilot Hole

Analysis of Variance for Gouge Nu
Source     DF        SS        MS        F        P
Pilot Ho    1      3.08      3.08     2.02    0.159
Error      92    140.41      1.53
Total      93    143.49
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
No Pilot   46     1.304     1.030  (-----------*------------)
Pilot Ho   48     1.667     1.404              (-----------*----------)
                                   ---------+---------+---------+-------
Pooled StDev =    1.235                   1.20      1.50      1.80


One-way ANOVA: Gouge Number versus Bit Length

Analysis of Variance for Gouge Nu
Source     DF        SS        MS        F        P
Bit Leng    1      0.68      0.68     0.44    0.509
Error      92    142.81      1.55
Total      93    143.49
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
Long       47     1.404     1.077   (-------------*-------------)
Short      47     1.574     1.395          (-------------*-------------)
                                   ---------+---------+---------+-------
Pooled StDev =    1.246                   1.25      1.50      1.75


One-way ANOVA: Gouge Number versus Bit Condition

Analysis of Variance for Gouge Nu
Source     DF        SS        MS        F        P
Bit Cond    1      4.26      4.26     2.81    0.097
Error      92    139.23      1.51
Total      93    143.49
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
New        47     1.277     1.057  (---------*----------)
Old        47     1.702     1.382             (----------*---------)
                                   ----+---------+---------+---------+--
Pooled StDev =    1.230               1.05      1.40      1.75      2.10

One-way ANOVA: Gouge Number versus Pressure

Analysis of Variance for Gouge Nu
Source     DF        SS        MS        F        P
Pressure    1      0.27      0.27     0.17    0.679
Error      92    143.22      1.56
Total      93    143.49
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --------+---------+---------+--------
High       46     1.435     1.515   (-------------*-------------)
Low        48     1.542     0.922       (--------------*-------------)
                                   --------+---------+---------+--------
Pooled StDev =    1.248                  1.25      1.50      1.75
```

```
One-way ANOVA: Gouge Number versus Bit Speed

Analysis of Variance for Gouge Nu
Source     DF        SS        MS        F        P
Bit Spee    1      0.09      0.09     0.06    0.806
Error      92    143.39      1.56
Total      93    143.49
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Full       48     1.458     1.352  (-------------*--------------)
Stopped    46     1.522     1.130    (--------------*-------------)
                                   ------+---------+---------+---------+
Pooled StDev =    1.248                1.25      1.50      1.75      2.00
```

Machine-Drilled Hole Quality

```
One-way ANOVA: Roughness versus Pilot

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Pilot       1  0.000043  0.000043     0.06    0.804
Error      22  0.014916  0.000678
Total      23  0.014959
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
No Pilot   12    1.0736    0.0310  (---------------*--------------)
Pilot Ho   12    1.0763    0.0198     (--------------*---------------)
                                   --+---------+---------+---------+----
Pooled StDev =   0.0260            1.060     1.070     1.080     1.090


One-way ANOVA: Roughness versus Length

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Length      1  0.004782  0.004782    10.34    0.004
Error      22  0.010177  0.000463
Total      23  0.014959
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
Long       12    1.0891    0.0263                     (--------*--------)
Short      12    1.0608    0.0152   (-------*--------)
                                   --+---------+---------+---------+----
Pooled StDev =   0.0215            1.050     1.065     1.080     1.095


One-way ANOVA: Roughness versus Condition

Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Conditio    1  0.000929  0.000929     1.46    0.240
Error      22  0.014030  0.000638
Total      23  0.014959
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
New        12    1.0687    0.0134  (------------*-----------)
Old        12    1.0812    0.0331           (------------*------------)
                                   --+---------+---------+---------+----
Pooled StDev =   0.0253            1.056     1.068     1.080     1.092
```

One-way ANOVA: Roughness versus Feedrate

```
Analysis of Variance for Roughnes
Source     DF        SS        MS        F        P
Feedrate    1  0.000201  0.000201     0.30    0.589
Error      22  0.014758  0.000671
Total      23  0.014959
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
High       12    1.0779    0.0284        (---------------*--------------)
Low        12    1.0721    0.0231   (--------------*---------------)
                                   ----+---------+---------+---------+--
Pooled StDev =   0.0259              1.060     1.070     1.080     1.090
```

One-way ANOVA: Conicality versus Pilot

```
Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Pilot       1     62.40     62.40    14.92    0.001
Error      22     92.04      4.18
Total      23    154.45
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
No Pilot   12     3.925     2.798                      (-------*------)
Pilot Ho   12     0.700     0.732   (------*-------)
                                   ----+---------+---------+---------+--
Pooled StDev =    2.045              0.0       1.6       3.2       4.8
```

One-way ANOVA: Conicality versus Length

```
Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Length      1     17.51     17.51     2.81    0.108
Error      22    136.94      6.22
Total      23    154.45
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
Long       12     3.167     3.355             (---------*---------)
Short      12     1.458     1.091   (---------*---------)
                                   -+---------+---------+---------+-----
Pooled StDev =    2.495           0.0       1.5       3.0       4.5
```

One-way ANOVA: Conicality versus Condition

```
Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Conditio    1      2.60      2.60     0.38    0.546
Error      22    151.85      6.90
Total      23    154.45
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
New        12     2.642     3.320        (------------*------------)
Old        12     1.983     1.668  (-------------*------------)
                                   -------+---------+---------+---------
Pooled StDev =    2.627                 1.2       2.4       3.6
```

One-way ANOVA: Conicality versus Feedrate

```
Analysis of Variance for Conicali
Source     DF        SS        MS        F        P
Feedrate    1     10.80     10.80     1.65    0.212
Error      22    143.65      6.53
Total      23    154.45
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----------+---------+---------+------
High       12     1.642     1.872   (------------*-----------)
Low        12     2.983     3.091              (------------*------------)
                                   ----------+---------+---------+------
Pooled StDev =    2.555                     1.2       2.4       3.6
```

One-way ANOVA: Angle versus Pilot

```
Analysis of Variance for Angle
Source     DF        SS        MS        F        P
Pilot       1      49.6      49.6     1.61    0.218
Error      22     679.7      30.9
Total      23     729.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
No Pilot   12     6.033     6.272            (----------*----------)
Pilot Ho   12     3.158     4.738  (-----------*----------)
                                   -+---------+---------+---------+-----
Pooled StDev =    5.558           0.0       3.0       6.0       9.0
```

One-way ANOVA: Angle versus Length

```
Analysis of Variance for Angle
Source     DF        SS        MS        F        P
Length      1      84.0      84.0     2.86    0.105
Error      22     645.3      29.3
Total      23     729.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
Long       12     6.467     6.270              (----------*---------)
Short      12     2.725     4.399  (----------*----------)
                                   --+---------+---------+---------+----
Pooled StDev =    5.416            0.0       3.0       6.0       9.0
```

One-way ANOVA: Angle versus Condition

```
Analysis of Variance for Angle
Source     DF        SS        MS        F        P
Conditio    1      21.1      21.1     0.66    0.427
Error      22     708.2      32.2
Total      23     729.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
New        12     5.533     6.489          (------------*-------------)
Old        12     3.658     4.719  (-------------*------------)
                                   ---------+---------+---------+-------
Pooled StDev =    5.674                    2.5       5.0       7.5
```

One-way ANOVA: Angle versus Feedrate

```
Analysis of Variance for Angle
Source     DF        SS        MS        F        P
Feedrate    1       0.4       0.4     0.01    0.913
Error      22     728.9      33.1
Total      23     729.3
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
High       12     4.725     4.598   (-----------------*----------------)
Low        12     4.467     6.717  (----------------*-----------------)
                                   -----+---------+---------+---------+-
Pooled StDev =    5.756               2.0       4.0       6.0       8.0
```

One-way ANOVA: Number versus Pilot

```
Analysis of Variance for Number
Source     DF        SS        MS        F        P
Pilot       1      8.17      8.17     3.65    0.069
Error      22     49.17      2.23
Total      23     57.33
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
No Pilot   12     1.917     1.730                (----------*----------)
Pilot Ho   12     0.750     1.215  (----------*-----------)
                                   --+---------+---------+---------+----
Pooled StDev =    1.495            0.00      0.80      1.60      2.40
```

One-way ANOVA: Number versus Length

```
Analysis of Variance for Number
Source     DF        SS        MS        F        P
Length      1      2.67      2.67     1.07    0.311
Error      22     54.67      2.48
Total      23     57.33
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----------+---------+---------+------
Long       12     1.667     1.435           (-------------*------------)
Short      12     1.000     1.706   (------------*-------------)
                                   ----------+---------+---------+------
Pooled StDev =    1.576                    0.70      1.40      2.10
```

One-way ANOVA: Number versus Condition

```
Analysis of Variance for Number
Source     DF        SS        MS        F        P
Conditio    1      0.00      0.00     0.00    1.000
Error      22     57.33      2.61
Total      23     57.33
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
New        12     1.333     1.670  (---------------*---------------)
Old        12     1.333     1.557  (---------------*---------------)
                                   ----+---------+---------+---------+--
Pooled StDev =    1.614              0.60      1.20      1.80      2.40
```

```
One-way ANOVA: Number versus Feedrate

Analysis of Variance for Number
Source     DF        SS        MS        F        P
Feedrate    1      8.17      8.17     3.65    0.069
Error      22     49.17      2.23
Total      23     57.33
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
High       12     1.917     1.730                (----------*----------)
Low        12     0.750     1.215  (----------*-----------)
                                   --+---------+---------+---------+----
Pooled StDev =    1.495            0.00      0.80      1.60      2.40
```

Exit Burrs

Curling Burr

One-way ANOVA: C versus Operator

```
Analysis of Variance for C
Source     DF        SS        MS        F        P
Operator    2    13.078     6.539    19.08    0.000
Error     116    39.746     0.343
Total     118    52.824
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ---+---------+---------+---------+---
Experien   48    0.4792    0.7143            (---*---)
Machine    24    0.9583    0.7506                      (-----*-----)
Novice     47    0.0638    0.2471 (----*---)
                                  ---+---------+---------+---------+---
Pooled StDev =   0.5854            0.00      0.40      0.80      1.20
```

One-way ANOVA: C versus Pilot Hole

```
Analysis of Variance for C
Source     DF        SS        MS        F        P
Pilot Ho    1     1.996     1.996     4.59    0.034
Error     117    50.827     0.434
Total     118    52.824
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev -----+---------+---------+---------+-
No Pilot   59    0.5424    0.6778               (-------*--------)
Pilot Ho   60    0.2833    0.6402  (-------*--------)
                                  -----+---------+---------+---------+-
Pooled StDev =   0.6591               0.20      0.40      0.60      0.80
```

One-way ANOVA: C versus Bit Length

```
Analysis of Variance for C
Source     DF        SS        MS        F        P
Bit Leng    1     0.620     0.620     1.39    0.241
Error     117    52.204     0.446
Total     118    52.824
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ---------+---------+---------+-------
Long       60    0.4833    0.7009           (----------*-----------)
Short      59    0.3390    0.6327 (-----------*----------)
                                  ---------+---------+---------+-------
Pooled StDev =   0.6680                    0.30      0.45      0.60
```

```
One-way ANOVA: C versus Bit Condition

Analysis of Variance for C
Source     DF        SS        MS        F        P
Bit Cond    1     0.003     0.003     0.01    0.936
Error     117    52.821     0.451
Total     118    52.824
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
New        60    0.4167    0.6712   (-----------------*----------------)
Old        59    0.4068    0.6726  (-----------------*----------------)
                                   -------+---------+---------+---------
Pooled StDev =   0.6719                 0.30      0.40      0.50


One-way ANOVA: C versus Pressure

Analysis of Variance for C
Source     DF        SS        MS        F        P
Pressure    1     0.056     0.056     0.12    0.724
Error     117    52.767     0.451
Total     118    52.824
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
High       59    0.3898    0.6952  (-------------*-------------)
Low        60    0.4333    0.6475     (-------------*-------------)
                                   --+---------+---------+---------+----
Pooled StDev =   0.6716            0.24      0.36      0.48      0.60


One-way ANOVA: C versus Bit Speed

Analysis of Variance for C
Source     DF        SS        MS        F        P
Bit Spee    1     1.008     1.008     2.28    0.134
Error     117    51.816     0.443
Total     118    52.824
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---+---------+---------+---------+---
Full       72    0.4861    0.6919                (---------*----------)
Stopped    47    0.2979    0.6226  (------------*------------)
                                   ---+---------+---------+---------+---
Pooled StDev =   0.6655             0.15      0.30      0.45      0.60
```

Triangular Burr

One-way ANOVA: T versus Operator

```
Analysis of Variance for T
Source     DF        SS        MS        F        P
Operator    2     1.982     0.991     1.73    0.182
Error     116    66.573     0.574
Total     118    68.555
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Experien   48    0.6250    0.7330    (--------*--------)
Machine    24    0.9167    0.7173            (------------*-----------)
Novice     47    0.5745    0.8007  (--------*--------)
                                  ------+---------+---------+---------+
Pooled StDev =   0.7576                0.50      0.75      1.00      1.25
```

One-way ANOVA: T versus Pilot Hole

```
Analysis of Variance for T
Source     DF        SS        MS        F        P
Pilot Ho    1    17.524    17.524    40.18    0.000
Error     117    51.031     0.436
Total     118    68.555
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
No Pilot   59    1.0508    0.7526                            (-----*-----)
Pilot Ho   60    0.2833    0.5552   (----*-----)
                                  -------+---------+---------+---------
Pooled StDev =   0.6604                 0.30      0.60      0.90
```

One-way ANOVA: T versus Bit Length

```
Analysis of Variance for T
Source     DF        SS        MS        F        P
Bit Leng    1     0.113     0.113     0.19    0.661
Error     117    68.442     0.585
Total     118    68.555
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
Long       60    0.6333    0.7357  (------------*------------)
Short      59    0.6949    0.7934      (------------*------------)
                                  -+---------+---------+---------+-----
Pooled StDev =   0.7648           0.45      0.60      0.75      0.90
```

```
One-way ANOVA: T versus Bit Condition

Analysis of Variance for T
Source     DF        SS        MS        F        P
Bit Cond    1     0.001     0.001     0.00    0.968
Error     117    68.554     0.586
Total     118    68.555
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
New        60    0.6667    0.7739   (----------------*---------------)
Old        59    0.6610    0.7568   (---------------*----------------)
                                  --+---------+---------+---------+----
Pooled StDev =   0.7655            0.48      0.60      0.72      0.84


One-way ANOVA: T versus Pressure

Analysis of Variance for T
Source     DF        SS        MS        F        P
Pressure    1     0.584     0.584     1.01    0.318
Error     117    67.971     0.581
Total     118    68.555
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
High       59    0.5932    0.7455  (-------------*------------)
Low        60    0.7333    0.7782           (------------*------------)
                                  ----+---------+---------+---------+--
Pooled StDev =   0.7622              0.45      0.60      0.75      0.90


One-way ANOVA: T versus Bit Speed

Analysis of Variance for T
Source     DF        SS        MS        F        P
Bit Spee    1     0.051     0.051     0.09    0.769
Error     117    68.504     0.586
Total     118    68.555
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
Full       72    0.6806    0.7659         (--------------*--------------)
Stopped    47    0.6383    0.7640   (-----------------*------------------)
                                  ------+---------+---------+---------+
Pooled StDev =   0.7652                0.48      0.60      0.72      0.84
```

Bulge Burr

One-way ANOVA: B versus Operator

```
Analysis of Variance for B
Source     DF        SS        MS        F        P
Operator    2     3.674     1.837     4.02    0.020
Error     116    52.965     0.457
Total     118    56.639
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
Experien   48    0.5625    0.7964                    (------*-----)
Machine    24    0.0833    0.2823   (--------*--------)
Novice     47    0.4043    0.6808               (-----*------)
                                   -------+---------+---------+---------
Pooled StDev =   0.6757                 0.00      0.30      0.60
```

One-way ANOVA: B versus Pilot Hole

```
Analysis of Variance for B
Source     DF        SS        MS        F        P
Pilot Ho    1     6.400     6.400    14.91    0.000
Error     117    50.238     0.429
Total     118    56.639
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----------+---------+---------+------
No Pilot   59    0.1695    0.3784  (------*------)
Pilot Ho   60    0.6333    0.8431                    (-----*------)
                                   ----------+---------+---------+------
Pooled StDev =   0.6553                    0.25      0.50      0.75
```

One-way ANOVA: B versus Bit Length

```
Analysis of Variance for B
Source     DF        SS        MS        F        P
Bit Leng    1     0.001     0.001     0.00    0.958
Error     117    56.637     0.484
Total     118    56.639
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --------+---------+---------+--------
Long       60    0.4000    0.6689  (-----------------*-----------------)
Short      59    0.4068    0.7220   (-----------------*-----------------)
                                   --------+---------+---------+--------
Pooled StDev =   0.6958                  0.30      0.40      0.50
```

One-way ANOVA: B versus Bit Condition

```
Analysis of Variance for B
Source     DF        SS        MS        F        P
Bit Cond    1     0.109     0.109     0.23    0.636
Error     117    56.530     0.483
Total     118    56.639
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
New        60    0.4333    0.6979       (--------------*--------------)
Old        59    0.3729    0.6923  (--------------*--------------)
                                   ----+---------+---------+---------+--
Pooled StDev =   0.6951              0.24      0.36      0.48      0.60
```

One-way ANOVA: B versus Pressure

```
Analysis of Variance for B
Source     DF        SS        MS        F        P
Pressure    1     2.846     2.846     6.19    0.014
Error     117    53.792     0.460
Total     118    56.639
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
High       59    0.5593    0.7938                  (--------*--------)
Low        60    0.2500    0.5407   (-------*--------)
                                   -------+---------+---------+---------
Pooled StDev =   0.6781                 0.20      0.40      0.60
```

One-way ANOVA: B versus Bit Speed

```
Analysis of Variance for B
Source     DF        SS        MS        F        P
Bit Spee    1     1.284     1.284     2.71    0.102
Error     117    55.355     0.473
Total     118    56.639
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
Full       72    0.3194    0.6241   (---------*---------)
Stopped    47    0.5319    0.7760             (-----------*------------)
                                   -+---------+---------+---------+-----
Pooled StDev =   0.6878           0.16      0.32      0.48      0.64
```

Fatigue Tests

Hand Drilling

One-way ANOVA: Nf versus Test Type

```
Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Test Typ    1 2.401E+09 2.401E+09    15.18    0.001
Error      21 3.321E+09 158165691
Total      22 5.722E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
Baseline    4     91438     28532               (--------*--------)
Hand Dri   19     64484      6989   (---*---)
                                  --+---------+---------+---------+----
Pooled StDev =    12576          60000     75000     90000    105000
```

One-way ANOVA: Ni1 versus Test Type

```
Analysis of Variance for Ni1
Source     DF        SS        MS        F        P
Test Typ    1 740644034 740644034     1.95    0.183
Error      15 5.688E+09 379225143
Total      16 6.429E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
Baseline    3     63500     44222     (---------------*---------------)
Hand Dri   14     46186     11692  (-------*------)
                                  -------+---------+---------+---------
Pooled StDev =    19474               45000     60000     75000
```

One-way ANOVA: Nf versus Bit Condition

```
Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Bit Cond    1  63588142  63588142     1.33    0.266
Error      17 815605233  47976778
Total      18 879193374
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
New        10     62748      5818  (-----------*----------)
Old         9     66412      7992          (-----------*-----------)
                                  -----+---------+---------+---------+-
Pooled StDev =     6927             60000     64000     68000     72000
```

```
One-way ANOVA: Nf versus Pilot Hole

Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Pilot Ho    1 162865502 162865502     3.87    0.066
Error      17 716327872  42136934
Total      18 879193374
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
No         10     61706      3384  (----------*----------)
Yes         9     67570      8755                (----------*----------)
                                  -------+---------+---------+---------
Pooled StDev =     6491               60000     64000     68000


One-way ANOVA: Ni versus Bit Condition

Analysis of Variance for Ni
Source     DF        SS        MS        F        P
Bit Cond    1 769602857 769602857     9.17    0.011
Error      12 1.008E+09  83971190
Total      13 1.777E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
New         7     38771      8502  (-------*------)
Old         7     53600      9780                (-------*------)
                                  ---------+---------+---------+-------
Pooled StDev =     9164                 40000     50000     60000


One-way ANOVA: Ni versus Pilot Hole

Analysis of Variance for Ni
Source     DF        SS        MS        F        P
Pilot Ho    1 105450060 105450060     0.76    0.401
Error      12 1.672E+09 139317257
Total      13 1.777E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ----+---------+---------+---------+--
No          6     43017      9854  (--------------*--------------)
Yes         8     48563     13018           (------------*------------)
                                  ----+---------+---------+---------+--
Pooled StDev =    11803            35000     42000     49000     56000


One-way ANOVA: Ni/Nf versus Bit Condition

Analysis of Variance for Ni/Nf
Source     DF        SS        MS        F        P
Bit Cond    1   0.06750   0.06750     7.15    0.022
Error      11   0.10387   0.00944
Total      12   0.17138
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
New         7   0.62627   0.11748   (-------*-------)
Old         6   0.77082   0.06491               (--------*--------)
                                  ------+---------+---------+---------+
Pooled StDev =  0.09718                0.60      0.70      0.80      0.90
```

```
One-way ANOVA: Nf-Ni versus Bit Condition

Analysis of Variance for Nf-Ni
Source     DF        SS        MS        F        P
Bit Cond    1 190573883 190573883     5.40    0.040
Error      11 388187646  35289786
Total      12 578761529
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ----------+---------+---------+------
New         7     23021      7465                (---------*---------)
Old         6     15341      3282 (----------*---------)
                                  ----------+---------+---------+------
Pooled StDev =     5941                 15000     20000     25000


One-way ANOVA: Ni/Nf versus Pilot Hole

Analysis of Variance for Ni/Nf
Source     DF        SS        MS        F        P
Pilot Ho    1    0.0118    0.0118     0.82    0.385
Error      11    0.1595    0.0145
Total      12    0.1714
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ---+---------+---------+---------+---
No          5    0.6548    0.1029 (--------------*--------------)
Yes         8    0.7169    0.1294            (-----------*----------)
                                  ---+---------+---------+---------+---
Pooled StDev =   0.1204             0.560     0.640     0.720     0.800


One-way ANOVA: Nf-Ni versus Pilot Hole

Analysis of Variance for Nf-Ni
Source     DF        SS        MS        F        P
Pilot Ho    1  17467024  17467024     0.34    0.570
Error      11 561294505  51026773
Total      12 578761529
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ----+---------+---------+---------+--
No          5     20943      5940   (-------------*-------------)
Yes         8     18560      7747 (----------*----------)
                                  ----+---------+---------+---------+--
Pooled StDev =     7143            15000     20000     25000     30000


One-way ANOVA: Ni2-Ni1 versus Bit Cond

Analysis of Variance for Ni2-Ni1
Source     DF        SS        MS        F        P
Bit Cond    1 101529167 101529167     2.40    0.153
Error      10 423540000  42354000
Total      11 525069167
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev -+---------+---------+---------+-----
New         7     11900      7910               (----------*----------)
Old         5      6000      3468 (------------*------------)
                                  -+---------+---------+---------+-----
Pooled StDev =     6508             0      5000     10000     15000
```

```
One-way ANOVA: Ni2-Ni1 versus Pilot Hole

Analysis of Variance for Ni2-Ni1
Source     DF        SS        MS        F        P
Pilot Ho    1  14006881  14006881     0.27    0.612
Error      10 511062286  51106229
Total      11 525069167
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
No          5     10720      3685    (-------------*--------------)
Yes         7      8529      8725  (-----------*-----------)
                                  -----+---------+---------+---------+-
Pooled StDev =     7149              5000     10000     15000     20000


One-way ANOVA: Ni2-Ni1/Nf versus Bit Cond

Analysis of Variance for Ni2-Ni1/
Source     DF        SS        MS        F        P
Bit Cond    1    0.0277    0.0277     2.71    0.131
Error      10    0.1024    0.0102
Total      11    0.1301
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
New         7    0.1921    0.1210               (----------*----------)
Old         5    0.0946    0.0602  (------------*-----------)
                                  -+---------+---------+---------+-----
Pooled StDev =   0.1012           0.000     0.080     0.160     0.240


One-way ANOVA: Ni2-Ni1/Nf versus Pilot Hole

Analysis of Variance for Ni2-Ni1/
Source     DF        SS        MS        F        P
Pilot Ho    1    0.0055    0.0055     0.44    0.523
Error      10    0.1246    0.0125
Total      11    0.1301
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
No          5    0.1767    0.0625      (---------------*---------------)
Yes         7    0.1335    0.1348   (------------*------------)
                                  -----+---------+---------+---------+-
Pooled StDev =   0.1116               0.070     0.140     0.210     0.280
```

```
One-way ANOVA: Nf versus Description 2

Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Descript    3 271261038  90420346     2.23    0.127
Error      15 607932336  40528822
Total      18 879193374
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
NN          5     60947      4474  (--------*--------)
NY          5     64549      6931        (-------*--------)
ON          5     62465      2075     (-------*--------)
OY          4     71345     10303                (---------*---------)
                                  --+---------+---------+---------+----
Pooled StDev =     6366          56000     63000     70000     77000


One-way ANOVA: Ni versus Description 2

Analysis of Variance for Ni
Source     DF        SS        MS        F        P
Descript    3 921252976 307084325     3.59    0.054
Error      10 856004167  85600417
Total      13 1.777E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
NN          3     37700      8227  (---------*---------)
NY          4     39575      9871    (--------*--------)
ON          3     48333      9500          (---------*---------)
OY          4     57550      9088                   (--------*--------)
                                  ---------+---------+---------+-------
Pooled StDev =     9252                 36000     48000     60000


One-way ANOVA: Ni/Nf versus Description 2

Analysis of Variance for Ni/Nf
Source     DF        SS        MS        F        P
Descript    3   0.08223   0.02741     2.77    0.103
Error       9   0.08914   0.00990
Total      12   0.17138
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
NN          3   0.62413   0.12489  (----------*----------)
NY          4   0.62787   0.13113   (--------*---------)
ON          2   0.70080   0.06435     (------------*-------------)
OY          4   0.80583   0.02721                  (--------*---------)
                                  ---------+---------+---------+-------
Pooled StDev =  0.09952                  0.60      0.72      0.84
```

```
One-way ANOVA: Nf-Ni versus Description 2

Analysis of Variance for Nf-Ni
Source     DF        SS        MS        F        P
Descript    3 220100139  73366713     1.84    0.210
Error       9 358661390  39851266
Total      12 578761529
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -+---------+---------+---------+-----
NN          3     22616      7494             (----------*-----------)
NY          4     23325      8586               (---------*----------)
ON          2     18432      2794    (-------------*-------------)
OY          4     13795      2406  (---------*---------)
                                  -+---------+---------+---------+-----
Pooled StDev =     6313          7000     14000     21000     28000


One-way ANOVA: Nf versus Factors

Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Factors     4 2.672E+09 668009939     3.94    0.018
Error      18 3.050E+09 169456582
Total      22 5.722E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ----------+---------+---------+------
BL          4     91438     28532                    (-------*--------)
NN          5     60947      4474  (-------*-------)
NY          5     64549      6931    (------*-------)
ON          5     62465      2075  (-------*-------)
OY          4     71345     10303       (--------*-------)
                                  ----------+---------+---------+------
Pooled StDev =    13018                 64000     80000     96000


One-way ANOVA: Nf versus Test Type

Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Test Typ    1 7.372E+12 7.372E+12     9.66    0.021
Error       6 4.581E+12 7.635E+11
Total       7 1.195E+13
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
Overload    4   1972801   1235701                  (-------*--------)
Underloa    4     52871      4130  (-------*--------)
                                  ---------+---------+---------+-------
Pooled StDev =   873777                   0   1200000   2400000
```

```
One-way ANOVA: Nf versus Orientation

Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Orientat    1 7.361E+11 7.361E+11     0.39    0.553
Error       6 1.122E+13 1.870E+12
Total       7 1.195E+13
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ---------+---------+---------+-------
LT          4    709500    917576  (-------------*-------------)
TL          4   1316172   1702081       (-------------*-------------)
                                  ---------+---------+---------+-------
Pooled StDev =  1367301                    0   1200000   2400000



Results for: 17.5 ksi As-Drilled

One-way ANOVA: Nf versus Test Type

Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Test Typ    1 7.979E+10 7.979E+10     4.75    0.061
Error       8 1.344E+11 1.679E+10
Total       9 2.141E+11
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ----+---------+---------+---------+--
Hand Dri    4    100795      8445  (---------*---------)
Machine     6    283135    163791               (-------*-------)
                                  ----+---------+---------+---------+--
Pooled StDev =   129591                0    150000    300000    450000


One-way ANOVA: Ni versus Test Type

Analysis of Variance for Ni
Source     DF        SS        MS        F        P
Test Typ    1 4.808E+10 4.808E+10     2.64    0.155
Error       6 1.092E+11 1.820E+10
Total       7 1.573E+11
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev --+---------+---------+---------+----
Hand Dri    2     59350      7000 (---------------*---------------)
Machine     6    238383    147753                   (--------*--------)
                                  --+---------+---------+---------+----
Pooled StDev =   134910        -150000         0    150000    300000
```

```
One-way ANOVA: Ni/Nf versus Test Type

Analysis of Variance for Ni/Nf
Source     DF        SS        MS        F        P
Test Typ    1   0.06942   0.06942    20.32    0.004
Error       6   0.02050   0.00342
Total       7   0.08992
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
Hand Dri    2   0.62345   0.03444   (-------*-------)
Machine     6   0.83858   0.06214                       (----*----)
                                  -------+---------+---------+---------
Pooled StDev =  0.05845                0.60      0.72      0.84


One-way ANOVA: Nf-Ni versus Test Type

Analysis of Variance for Nf-Ni
Source     DF        SS        MS        F        P
Test Typ    1 123515288 123515288     0.25    0.635
Error       6 2.971E+09 495186116
Total       7 3.095E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
Hand Dri    2     35677      1017   (--------------*---------------)
Machine     6     44751     24372            (--------*--------)
                                  --+---------+---------+---------+----
Pooled StDev =    22253              0     25000     50000     75000


One-way ANOVA: Nf-Ni/Nf versus Test Type

Analysis of Variance for Nf-Ni/Nf
Source     DF        SS        MS        F        P
Test Typ    1   0.06940   0.06940    20.30    0.004
Error       6   0.02051   0.00342
Total       7   0.08992
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
Hand Dri    2   0.37652   0.03441                (-------*--------)
Machine     6   0.16142   0.06218   (---*----)
                                  --+---------+---------+---------+----
Pooled StDev =  0.05847           0.12      0.24      0.36      0.48
```

Results for: 17.5 ksi Machine Drilling

One-way ANOVA: Nf versus Params

```
Analysis of Variance for Nf
Source     DF        SS        MS        F        P
Params      1 5.123E+10 5.123E+10     2.47    0.191
Error       4 8.291E+10 2.073E+10
Total       5 1.341E+11
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ---+---------+---------+---------+---
NY          3    190734     52755  (-----------*----------)
OY          3    375535    196652           (-----------*----------)
                                  ---+---------+---------+---------+---
Pooled StDev =   143971               0    200000    400000    600000
```

One-way ANOVA: Ni versus Params

```
Analysis of Variance for Ni
Source     DF        SS        MS        F        P
Params      1 3.341E+10 3.341E+10     1.76    0.255
Error       4 7.575E+10 1.894E+10
Total       5 1.092E+11
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ----+---------+---------+---------+--
NY          3    163767     39708 (-------------*-------------)
OY          3    313000    190520           (-------------*------------)
                                  ----+---------+---------+---------+--
Pooled StDev =   137613                0    160000    320000    480000
```

One-way ANOVA: Nf-Ni versus Params

```
Analysis of Variance for Nf-Ni
Source     DF        SS        MS        F        P
Params      1 1.898E+09 1.898E+09     7.08    0.056
Error       4 1.072E+09 268114709
Total       5 2.970E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ----------+---------+---------+------
NY          3     26967     14277 (----------*---------)
OY          3     62535     18232                (---------*----------)
                                  ----------+---------+---------+------
Pooled StDev =    16374                  25000     50000     75000
```

```
One-way ANOVA: Ni/Nf versus Params

Analysis of Variance for Ni/Nf
Source     DF        SS        MS        F        P
Params      1   0.00377   0.00377     0.97    0.381
Error       4   0.01554   0.00389
Total       5   0.01931
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ---------+---------+---------+-------
NY          3   0.86363   0.04089         (-------------*--------------)
OY          3   0.81353   0.07810  (-------------*-------------)
                                  ---------+---------+---------+-------
Pooled StDev =  0.06234                  0.770     0.840     0.910


One-way ANOVA: Nf-Ni/Nf versus Params

Analysis of Variance for Nf-Ni/Nf
Source     DF        SS        MS        F        P
Params      1   0.00377   0.00377     0.97    0.381
Error       4   0.01556   0.00389
Total       5   0.01933
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev -----+---------+---------+---------+-
NY          3   0.13635   0.04093 (-------------*--------------)
OY          3   0.18649   0.07813        (--------------*-------------)
                                  -----+---------+---------+---------+-
Pooled StDev =  0.06237               0.070     0.140     0.210     0.280


One-way ANOVA: Ni2-Ni1 versus Params

Analysis of Variance for Ni2-Ni
Source     DF        SS        MS        F        P
Params      1 2.170E+09 2.170E+09     4.67    0.097
Error       4 1.857E+09 464151667
Total       5 4.026E+09
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev -------+---------+---------+---------
NY          3     15100     20191  (----------*-----------)
OY          3     53133     22817             (-----------*----------)
                                  -------+---------+---------+---------
Pooled StDev =    21544                  0     30000     60000


One-way ANOVA: Ni2-Ni1/Nf-Ni1 versus Params

Analysis of Variance for Ni2-Ni/N
Source     DF        SS        MS        F        P
Params      1     0.252     0.252     2.44    0.194
Error       4     0.414     0.104
Total       5     0.666
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev ---+---------+---------+---------+---
NY          3    0.4112    0.4264 (------------*------------)
OY          3    0.8212    0.1588            (------------*-----------)
                                  ---+---------+---------+---------+---
Pooled StDev =   0.3217             0.00      0.40      0.80      1.20
```